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Preface

The hydraulic prototype tests and subsequent numerical modeling presented in this report were performed under the sponsorship of the U.S. Army Engineer District, St. Paul. This study was authorized by the Lakes and Rivers Division, U.S. Army Corps of Engineers, 13 January 2000.

1   Introduction

Background

Lock and Dam 1 is located at Mississippi River mile 847.6, above the mouth of the Ohio River between the cities of St. Paul and Minneapolis, Minnesota (Figure 1). The original Lock and Dam 1 was opened to navigation in July 1917. Extensive damage to the structure in 1929 required construction of a new lock. New lock construction was completed in September 1930. A second lock, landward from the first, was completed in May 1932. The lock chamber is 17.1 m (56 ft) by 121.9 m (400 ft) and the lock has a lift of 11.6 m (37.9 ft). Rehabilitation of the landward lock, the subject of this study, was completed in 1981. Various design features of the filling and emptying system of the landward lock were developed in a 1:25-scale hydraulic model study (Ables 1979). The rehabilitation modifications consisted of the construction of new intake manifolds, lowering of the culvert soffit and changing the shape of the filling and emptying system culverts, construction of new sidewall ports, replacement of the original stoney valves with reverse tainter valves, and construction of new outlet manifolds. Details of the filling and emptying system are provided on the plan and elevation drawing of Figure 2. Recently, operation of the reverse tainter valves was switched from a hydraulic cylinder to a steel rope and winch system.

The project, due to its age, has developed some limitations to the upper pool drawdown capabilities. The crest of the dam has been raised 0.61 m (2 ft, from el 723.1 to el 725.1)[1] by the installation of an inflatable rubber bladder to increase the head on the adjacent hydropower plant. The next lowest outlet for discharge below the dam crest is the invert elevation of the turbine inlets, which is at el 710.0. The estimated discharge that can be released through each turbine is 110 cms (4,000 cfs). The absolute lowest elevation of any flow outlets at the project is at the eight sluiceway intakes (el 697.1) which are located in the dam and adjacent to the powerhouse structure. However, of the eight sluiceways there are only two sluiceway gates that are operable, Gates 2 and 4. Gate 1 was permanently closed off

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[1]   All elevations (el) cited are in feet referenced to Mean Sea Level (1912 adjusted).

with a concrete bulkhead in 1950, and Gate 3 is inoperable as the result of deteriorated concrete around the gate frame, which was discovered during an inspection in 1992. Gate operating equipment for Gates 2, 3, and 4 was converted from a manual to a hydraulic mechanism several years ago. However, the operating machinery for Gates 5 through 8 was not converted to hydraulic and also has not been operated for an extended period of time. Successful operation of these sluiceways in an emergency situation is questionable. It is these limitations on available drawdown outlets that have prompted the consideration to use the lock culvert system for increasing available discharge capabilities under extreme emergency conditions.

Purpose and Scope

The purpose of this study is to determine what limitations must be placed on the use of the lock culvert system if used as a means of pool drawdown. Guidelines and operation procedures must be developed and documented to provide instruction for lock operators for lock culvert valve operation during an emergency. The hydraulic model study (Ables 1979) found that low pressures exist in the lock culvert during the unsteady flow of lock operations. The steady flow obtained during pool lowering could produce even lower pressures, which might induce cavitation in the culvert filling and emptying system. These conditions must be considered in any potential long-term operation of the lock system for releases other than normal lock operation. A numerical model study of the lock system would provide information for simulations of different head and tailwater conditions. Discharge and pressures for steady-state flows require model validation with prototype data for similar operating conditions. Information needed for numerical model validation included the upper and lower pool elevations, gate position, and lock culvert soffit pressures downstream of the filling and emptying valves.

Prior Model Study

A 1:25-scale lock model study was reported by Ables (1979) of the hydraulic improvements associated with the major rehabilitation undertaken in 1980 and completed in 1981. Improvements to the hydraulic filling and emptying system constituted significant departures from the existing design. A model study of the modified system was required to confirm the hydraulic adequacy of the modified lock system.

The model reproduced approximately 180 m (600 ft) of the upstream approach, the entire landward filling and emptying system including intakes, culvert tainter valves in longitudinal wall culverts, the interlaced outlet, and about 150 m (500 ft) of the downstream approach. While the physical model study investigated both the riverward and landward lock

systems, the current report specifically addresses evaluation of hydraulic conditions in the landward lock, exclusively.

Approach

Past hydraulic model studies have been supplemented with simulations using the Corps of Engineers' computer program H5320, LOCK FILLING AND EMPTYING—SYMMETRICAL SYSTEMS (Hebler and Neilson 1976). However, the limitations of H5320 inhibit its use in evaluating the discharge capability of the lock. H5320 is applicable only to symmetrical systems, and it does not reproduce the free-surface reaches of the upper and lower approaches and the lock chamber or the pressure and discharge in the filling and emptying manifolds. A numerical flow model, LOCKSIM (Schohl 1999), has been developed to serve as an improved evaluation tool for lock filling and emptying system designs. LOCKSIM couples the unsteady pressure-flow equations, which are applicable to the conduits within the system; with the free-surface equations describing the approach reservoirs, valve wells, and lock chamber. The model computes pressures and flow distributions throughout a lock system.

LOCKSIM simulates closed-conduit components such as culverts, reverse tainter valves, pipe losses, tees, and manifolds. Free-surface components include prismatic open channels, riverine channels, and water storage components (which can represent reverse tainter valve wells). Individual components from these lists are connected at nodes, where they share a common piezometric head.

Discharge and piezometric head in the pipe and free-surface channel components are computed by numerically solving partial differential equations for one-dimensional (1-D) unsteady flow. The water storage component is governed by an ordinary differential equation describing conservation of mass. The relationships between discharge and piezometric head difference for valves, check valves, and pipe losses are described by algebraic energy equations. The position of a valve is prescribed as a function of simulation time using tabulated data. Functions are also used for tee and manifold components, which simulate combining and dividing flow, to describe the variation of the branch headloss coefficients with the ratios of the individual branch discharges to the combined discharge. Available time-varying numerical results include pressure, hydraulic gradeline elevation, and discharge at all computational points. The stage, velocity, depth, top width, and channel area are provided at each computational point within the free-surface components, and the velocity, shear stress, and vapor cavity volume are given for each computational point within the closed-conduit components. The minimum pressures and cavitation indices in the wakes of reverse tainter valves are also computed.

2 Field Experiments

Measurements and Equipment

Pressure transducers were used to measure the water-surface elevation in the upper pool; the lock chamber, the lower pool, and the land-wall filling and emptying valve wells. Transducers were also mounted on the culvert soffit to measure the piezometric head downstream of the land-wall filling and emptying valves. Tiltometers were mounted on the right-culvert valves to record their movement. Transducer locations are shown on Figure 2.

The data acquisition system was set up in the service building. The cables for the pressure transducers and tiltometers installed at the upper pool, lock chamber, downstream pool, and culvert locations were routed along the upper land wall to the recording area in the service building (Figures 3 through 5). The cables were terminated at the data acquisition system shown in Figure 6.

A triaxial accelerometer, to monitor vibrations, was mounted on the intermediate lock wall (I-wall) that separates the two lock chambers. A mounting plate for the accelerometer was attached to the upper surface of the I-wall with epoxy adhesive and the accelerometer canister (Figure 7) was bolted to the mounting plate. Cables from the accelerometer were routed along the I-wall guardrail to the operation tower, up to the second level walkway, and back to the service building recording area.

Test Procedures and Conditions

The sequence for the lock operations performed during the data collection is listed in Table 1. A total of 18 data files were obtained during the data collection period. The following procedures for normal lock operations were followed for each period of data recording to provide consistency in the data collection and assurance that all instruments were zeroed to a known reference datum. Prior to any period of data collection, the miter gates (upper or lower, depending on the lock chamber water level)

were opened slightly to equalize the water level in the lock chamber and dissipate any water surface oscillations resulting from the previous operation. When the lock was empty (the water surface at the lower pool elevation), all instrument readings were set at zero for the existing lower pool water level elevation. The data acquisition system was activated to begin recording data for 30 sec to collect baseline information on all the instruments. The miter gates were closed, and the operation of the filling or emptying valves was initiated. Once the lock was empty or full, the miter gates were then opened slightly to equalize the water level in the lock chamber and to dissipate any water surface oscillations. When the lock chamber water surface appeared to be calm, data recording was stopped.

Throughout the data collection period, water levels for the upper pool, lock chamber, and lower pool were obtained from readout displays located in the operation building. Additional information was obtained by reading the staff gauges located on the land wall in each area. The observed readings are listed in Table 2 for the various lock operations. These values provide reference datum information to be applied to the recorded pressure transducer data in the upper pool, lock chamber, and lower pool prior to and after each data collection period.

Normal lock operations for filling and emptying cycles were monitored to observe the pressures, valve movements, and I-wall vibrations for the currently programmed valve movements and incremental valve movements. The current programmed lock operation for a filling cycle is for each fill valve to stop at 25-percent open for approximately 15 sec, continue opening, stop again at 50-percent open for approximately 60 sec, and then continue opening to 100 percent (see Figure 8). The observed total time for the valve operation is 157 sec. The current programmed operation slightly staggers the opening of the two fill valves. Table 3 illustrates the relation between valve opening in percent and degrees. During the empty cycle of the programmed lock operation, the opening of the empty valve is continuous from the closed position to the fully opened position. The empty-valve opening operation time was observed to be 83 sec. The incremental valve opening consists of opening the fill valve in 25-percent increments, holding for approximately 60 sec, proceeding to the next opening requiring a total of 4 min to reach the fully opened position (Figure 9). A 4-min valve time was recommended in the physical model study. During a normal lock filling operation, the culvert soffit pressures immediately downstream of the fill valve were observed to be lowest at valve openings of 50 percent (Figure 10). The greatest drawdown of the water level in the fill valve well was observed to occur at 100 percent valve openings (Figure 11).

Operations of the fill and empty valves were performed to determine the effect of closing the valves during the period of lowest pressures at the culvert soffit (Table 2; Tests 5 and 6). During these operations the valves were operated normally, except that immediately before the valves began to open from the 50-percent increment, closing procedures were initiated to simulate emergency valve closure operation. The data recorded by the

tiltometers indicated no potential problem with valve closure under these circumstances (Figures 12 and 13).

Nonnormal lock operations (Table 1) refer to conditions under which the lock structure might be used to provide additional discharge capacity during emergency pool drawdown procedures. These types of lock operations, as listed in Table 2, were conducted to determine the hydraulic conditions that result from the various configurations of fill valves, empty valves, and miter gates.

First flow release operation

The first of a series of flow releases using the lock culvert system was performed using the same operating procedures that had been used in previous operations for flow releases. Initially, a split-head differential is established between the upper pool and the water level in the lock chamber at the half-full level. (el 709.23). The fill valves and empty valves are set at the fully opened position. The empty-valve opening lagged 3 sec behind the fill-valve opening. During the initial part of the flow release operation, the fill valve remained in the fully opened position, and the water level in the lock chamber was controlled using the empty valve. During the latter part of the operation, adjustments to both of the valves were continuously made to maintain the water surface in the lock chamber at the half-full level. Figures 14 and 15 depict the time-history of this operation. The lowest pressure downstream of the empty valve was 3.54 m (11.6 ft, el 674.6) below the culvert soffit. The lowest pressure recorded downstream of the fill valve was 1.40 m (4.6 ft, el 690.8) above the culvert soffit. These low pressures were instantaneous responses to changes in the valve openings.

Second flow release operation

A second operation for flow release using the lock chamber was performed. For this operation, the lower miter gates were locked in the open position, the lock chamber water surface was at the lower pool elevation, the empty valves were closed, and then the fill valves were opened in increments. The first opening was set to 20 percent for approximately 7.5 min. The fill valve was then opened to 40 percent for the remainder of the operation (Figure 16). Fill valve openings above 40 percent were prohibited for safety reasons. A requirement to perform this type of operation is that the lower miter gates be locked in the open position by pinning them to the wall in the miter gate recesses. As a precautionary measure, this procedure is followed to prevent the gates from closing as a result of any significant flow forces in the lock chamber and gate recess areas. The flow patterns and resulting forces that could be generated from this type of operation could be significant enough to overpower the hydraulic operating system of the gate. If this were to occur, severe damage to the miter gates would result from the uncontrolled closing. The lowest pressures recorded at the culvert soffit below the fill valve were 3.75 m (12.3 ft, el 673.9) below the

culvert soffit and occurred when the valve went past the 40-percent open position. No significant pressure fluctuations were recorded during this operation. The average pressure at the 40-percent valve opening was 3.23 m (10.6 ft, el 675.6) below the culvert soffit.

Third flow release operation

A third flow release operation was performed similar to that when the lock chamber was initially half full, with the following changes. Initially, the lock chamber was full (pool el 726.6), the fill valve was set at the fully opened (100 percent) position, and the empty valve opened in 10-percent increments. Each incremental opening of the empty valve was held at that position for an average of 120 sec. Figures 17 through 19 present the time-history of the culvert pressures, lock chamber water-surface elevation, and the empty-valve openings for this flow release operation. Culvert soffit pressures below the fill valve followed closely and slightly lower than the lock chamber water-surface elevations. The lowest average pressure recorded below the fill valve was 3.96 m (13.0 ft) above the culvert soffit. No steady-state pressure conditions were reached at this location due to the continual lowering of the lock chamber water surface. The culvert soffit pressures below the empty valve changed with each increment of valve opening. The lowest average pressure below the empty valve was 3.05 m (10.0 ft) below the culvert soffit and occurred at the valve opening of 70 percent. No significant pressure fluctuations were evident in the recorded data.

A series of lock operations were then performed using only the land-wall culvert valves for the filling and emptying of the lock chamber. The valves were operated under two different conditions; valve openings with no programmed stops during the opening and openings of 25-percent increments over a 4-min time period. The results of lock operations with valves opened completely with no programmed stops are shown in Figures 20 through 23. During the lock-empty test, the lowest empty-valve culvert soffit pressure was 2.50 m (8.2 ft, el 678.0) below the culvert soffit occurring at a valve opening of 50 percent. The lowest fill-valve culvert soffit pressure during the lock filling operation was 4.36 m (14.3 ft, el 671.9) below the culvert soffit. The results of single-valve lock operations, filling and emptying, with the valves opened in 25-percent increments are shown in Figures 24 through 27. The lowest recorded culvert soffit pressures for the empty and fill operations were 2.74 m (9.0 ft, el 677.2) and 3.23 m (10.6 ft, el 675.6) below the culvert soffit, respectively.

In all the lock operations where the fill valve is at 100 percent open, there appears to be significant movement of the valve (3.3 deg or 0.15 m (0.5 ft)) as a result of the high velocities and the low head in the lock chamber as shown in Figure 28. This condition persists for a period of time (60 to 80 seconds) until sufficient water levels in the fill-valve well and lock chamber (el 712) were reached and the velocities at the valve decreased. Visual observations of the lift cable movement were noted during these

periods of valve movement. It was observed that the fill-valve lifting cable had significant movement in it. The cable moved approximately 8 to 10 cm (3 to 4 in.) back and forth. This condition may be the result of the valve lifting eye protruding into the flow below the elevation of the culvert soffit. Vibration of the empty-valve lifting cable was also observed during the lock emptying operations, although these conditions were not as extreme as those for the fill valve. Any long-term operation of the valves under these conditions should be avoided. It is recommended that modifications be made to increase the limit settings for the valve openings to raise the valve-lifting beam above the elevation of the culvert soffit.

As part of the overall data collection program, vibrations of the I-wall were monitored during all lock operations. During a previous emergency drawdown operation, project personnel detected significant vibrations of the I-wall. During the data collection effort for this report, the flow conditions that most closely resembled those from this previous operation are represented by lock operation item 2a, Table 1, herein.

No significant vibration levels were detected during the normal lock operations. Vibration levels were very low, ranging from 0.000 g's during the majority of the operations to 0.012 g's during the nonnormal lock operations. The acoustics from the air being drawn into the bulkhead slots and the valve wells were the most severe conditions observed during the various operations. This condition was especially evident during the single-valve lock fill operation. The air drawn into the bulkhead slot caused the steel cover plate to deflect approximately 1 to 2 cm (½ to ¾ in.). The noise level created by this operation was significantly higher and more disturbing than the structural vibration levels.

3   Model Applications

This study's principal objective was to construct a model of the Lock 1 system and then develop a steady-state operational scheme for passing flow through the system. A schematic showing the nodes and components of the LOCKSIM model is provided in Figure 29. The numerical model reproduced the entire filling and emptying system, including the intakes, valves, culverts, lock chamber, and outlets. Field data were used to quantify loss coefficients of the lock system. The resulting model was then tested by comparing model results with field data for additional operating conditions. Energy loss coefficients were determined for primary components of the system for which there is limited published data. Both the filling components and the emptying components of the lock system were validated with field data.

Model Parameters

Initial tests were conducted to determine the sensitivity of the model to selection of various constants. Two constants in particular were tested. The implicit weighting factor used in the Preissmann's four-point implicit scheme (Schohl 1999) and the time-step. LOCKSIM stability requires that the implicit weighting factor lie between 0.5 and 1.0. Best accuracy is achieved using values near 0.5, but values too near 0.5 can produce solutions having numerical oscillations. Larger values increase numerical damping, which reduces oscillations at the expense of accuracy. Typically, the implicit weight factor is specified between 0.55 and 0.7 (Schohl 1999). Normal lock filling and emptying simulations employed a time-step of 1.0 sec, and an implicit weighting factor of 0.55 provided sufficient stability. Numerical experiment simulations that were run with steady-state flow through both the filling and emptying systems indicated that model stability was best maintained using a time-step of 5.0 sec and an implicit weighting factor of 0.7.

The contraction coefficient, C_c, is a parameter used by LOCKSIM to calculate the piezometric head at the culvert soffit immediately downstream of the filling and emptying valves and the cavitation index, σ (discussed

further in Chapter 4), for the low-pressure region downstream of the valves. Published data quantifying the contraction coefficient show considerable scatter (Headquarters, U.S. Army Corps of Engineers (HQUSACE) 1975). The coefficient of contraction for flow downstream of the valves was specified as a polynomial function

$$C_c = 1.385\left(\frac{b}{B}\right)^4 - 4.2117\left(\frac{b}{B}\right)^3 + 4.178\left(\frac{b}{B}\right)^3 - 1.6123\left(\frac{b}{B}\right) + 0.8646 \tag{1}$$

where

C_c = the contraction coefficient

b = valve opening

B = culvert height at the valve

According to Schohl (1999), this relation describing C_c in terms of the relative valve opening is a best fit of the prototype data presented in EM 1110-2-1610, "Hydraulic Design of Lock Culvert Valves" (HQUSACE 1975). The contraction coefficient for a reverse tainter valve is very sensitive to the shape of the bottom edge of the valve. There is no universal description of contraction coefficients for reverse tainter valves. However, the values used for this study are believed to be adequate for estimating the lowest pressures at partial gate openings.

Filling System

Determination of loss coefficients

Single-valve lock operations were used to determine energy loss coefficients on the components for which no published data are available. Because of the empirical basis of 1-D models, a successful simulation requires accurate knowledge of coefficients. In particular, LOCKSIM computes head losses for flow-through components in the form

$$H_{Li} = K_i \frac{V_i^2}{2g} \tag{2}$$

where

H_L = headloss

i = a particular component

K = loss coefficient

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$V =$ velocity

$g =$ gravitational acceleration

Loss coefficients for many hydraulic components are well established and are readily available in the literature (e.g., Miller 1990). However, lock culvert system components are often unique to a particular project and the loss coefficients have not been determined. Field measurements are the solution to the problem of modeling a lock that has several unique components such as Lock 1. If a flow model, having physically reasonable coefficients, can reproduce conditions at which field data were obtained, then one can have confidence in the ability of a model to predict other flow conditions. This study uses two sets of field data (one for the filling system and one for the emptying system) to establish previously unknown loss coefficients. These coefficients are then used in modeling two other conditions (one of filling and one of emptying) for which field data are available. This process of determining loss coefficients followed by model testing with a separate set of field data is referred to as model validation.

The unknown coefficients were determined using the optimization techniques provided in the commercial software package iSIGHT.[1] This involved linking the LOCKSIM model of Lock 1 with iSIGHT. The optimization routine was developed to automatically change the specified coefficients in the LOCKSIM input file, execute the LOCKSIM program, read the flow solution, and compute error indicators. The error indicators were chosen to be the differences in computed and observed fill (or empty) time, pressure downstream of the valve, and the water surface in the valve well at critical times during the operation. The optimization scheme drives these error indicators toward zero by adjusting the specified energy loss coefficients. More than 500 LOCKSIM runs were completed in an automatic fashion for each (filling and emptying) system to establish the coefficients for the filling and emptying systems.

Determination of the loss coefficients for filling system components used the field data recorded as Test 18. The valve schedule for this single-valve filling operation (landside culvert) is presented in Figure 30. Particular emphasis was the determination of appropriate loss coefficient values for the intakes and the "chute" vertical transition. This transition involves two vertical curves and a 9.1-m (30-ft) drop in culvert elevation immediately upstream of the filling valves. The field data were used to establish the values of these loss coefficients. The results of the adjusted model are shown in Figures 31 through 33. The model reproduces the field data quite well except for the pressures downstream of the filling valve when the valve moves from closed to about 50 percent open. The model accurately captures the lowest pressures at valve openings greater than 50 percent. The loss coefficients determined from this process are provided in Table 4.

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[1] Engineous Software, Inc. No endorsement of this product is made or implied in this report.

Model testing

The coefficients used to describe the filling system were then tested by comparison with a stepped-dual valve filling operation. This is the Test 3 field data. This four-step dual valve test (see Figure 34 for valve schedule) was used, since no data for a normal dual-valve filling operation were available. Modeling a stepped-valve schedule is significantly more challenging than modeling a normal valve operation, yet the simulation results and the Test 3 data, presented in Figures 35 through 37, are in acceptable agreement. Again, the greatest error is in the pressures downstream of the filling valve for small valve openings. The errors are attributed to the contraction coefficient used to compute the pressures at the vena contracta. The stepped-valve operation magnifies this error because the valve is held at small openings over a significant portion of the valve operation time. The normal (continuous) valve openings would be modeled accurately.

Emptying System

Determination of loss coefficients

The loss coefficients associated with the emptying system were determined using the data of Test 12. The schedule for this single-valve emptying operation is presented in Figure 38. These runs were used to quantify loss coefficients for the sidewall ports acting as intakes, the transition from the manifold culvert to the valve culvert, and the outlet manifolds. Model results for the adjusted emptying system are provided in Figures 39 through 41.

The emptying valve never reached a fully opened position (i.e., $b/B = 1.0$). Rather, the field data show significant head loss across the valve, when in the fully opened position as shown in Figure 42, which is a plot of the pressure head at the empty-valve well and below the empty valve. Adjustment of the modeled maximum valve opening (b/B maximum) led to the conclusion that emptying valve reaches a maximum of 97 percent ($b/B = 0.97$).

Error in modeling the sidewall port manifold using diverging tee component is compensated at the transition and therefore, the transition coefficient is larger than expected. This results in the model producing the correct energy at the valve well.

The error-minimization process found that the loss coefficients that are reported in Table 5 are appropriate for the emptying-system components. The computed emptying curve and the pressures downstream of the emptying valve matched the field data well during the critical period of low pressure. As with the filling valves, the soffit pressures downstream of the empty valves are higher than those observed in the prototype for valve

openings less than 50 percent. The model pressures are in reasonable agreement with the field data at the time in which the pressures are lowest.

Model testing

The emptying system loss coefficients were tested by comparison with a field data set of a normal dual-valve emptying operation (Test 2). The Test 2 valve schedule is shown in Figure 43. The test results are shown in the time-history graphs provided in Figures 44 through 46. The model is conservative in estimation of low pressures downstream of the emptying valve. The model predicted pressures are slightly lower than the field data during the occurrence of peak minimum pressure. The error in the pressures downstream of the empty valves are attributed to the choice of contraction coefficient. The contraction coefficient used in the model had little effect on the peak minimum pressure but did produce a lag in the computed pressure magnitude timing versus the observed pressure data. This timing error should be of no consequence in computing the pressure below the valve in the steady-state flow conditions that will be examined in the pool-lowering evaluation.

4 Flow Passage through the Lock System

Discharge Rating for Pool Lowering

The steady-state discharge through the lock filling and emptying system is quantified with a discharge coefficient to provide a head-discharge relation in the form

$$Q = 2C_D A_V \sqrt{2gH} \tag{3}$$

where

$Q =$ discharge through the lock

$C_D =$ lock discharge coefficient

$A_V =$ valve area

$H =$ lock lift (difference in upper and lower pools)

The selection of valve area as representing the flow area is a common choice in lock design/evaluation and is the area used in EM 1110-2-1604 "Hydraulic Design of Navigation Locks" (HQUSACE 1995) to develop a system's lock coefficient. Steady-state solutions were computed by simulating 4,800 sec of lock operation beginning with the lock full and both the filling and emptying valves closed. First, the filling valves were fully opened in 83 sec; then the emptying valves were fully opened (actual $b/B =$ 97 percent as explained in Chapter 3) in 480 sec (Figure 47). The 83-sec valve time was the project's normal valve opening time (see valve schedule in Figure 30) and the 480-sec valve time was taken from the physical model study recommendations. As the chamber water surface fell, the flow evolved to a steady state with flow in the intakes and out the discharge laterals. Steady state was determined by continuity check of the lock system. When the difference in discharge in and out of the system was insignificant, the model was considered at steady state. Simulation results of the condition of an upper pool el 726.3 and a lower pool el 689.2 are presented

in Figures 48 through 50. The model results at steady state were then used to determine a discharge coefficient for the lock system. Table 6 provides the pool conditions simulated and summarizes the discharge rating results. A discharge-rating curve for the lock system is provided in Figure 51. The discharge coefficient for the lock system is constant for the heads evaluated in this study. The lock discharge coefficient, which was determined to be 0.55, can be used to compute other head/discharge relations for flow through the lock, within the range of lifts anticipated at the project.

These simulations show that although the steady-state pressures downstream of the filling and emptying valves are acceptable, pressures downstream of the emptying valves are quite low as the emptying valve is opened. The lowest pressures occur when the valve is between 50 and 70 percent open. These low pressures can lead to cavitation. The potential for cavitation is quantified using the cavitation index, σ, expressed as

$$\sigma = \frac{P + (P_a - P_v)}{V^2/2g} \qquad (4)$$

where

$P =$ gauge pressure head at the top of the vena contracta of the jet emerging from the partially open valve

$P_a =$ atmospheric pressure head

$P_v =$ vapor pressure head of water

$V =$ velocity in vena contracta of the jet emerging from the partially open valve

A value of 10.15 m (33.3 ft) is used for the term P_a - P_v. There has been much discussion regarding the cavitation index value that is associated with incipient cavitation in unvented systems (no air vent) as pointed out in EM 1110-2-1610 (HQUSACE 1975). A value of 0.61 has been used by many and this value is substantiated by the prototype study of Bay Springs Lock (McGee 1989). Paragraph 5-21 of EM 1110-2-1604 (HQUSACE 1995) states that "Any conditions that allow a cavitation parameter of less than 0.6 to develop is unacceptable." The air vents downstream of the valves at Lock 1 are in questionable condition. Therefore, maintaining a cavitation index above 0.61 is recommended whenever possible.

Valve Operation Optimization

Partial valve openings

Effort was next directed to developing an operation schedule that could reach the steady state without subjecting the lock to adverse pressure conditions. The pools modeled were an upper pool of el 726.3 and lower pool of el 687.2. First, simulations of lock operations were made with the lock chamber initially full and both filling and emptying valves closed. The emptying valves were then raised to the 60-percent (b/B) open position in 480 sec (Figure 52). Results of these calculations are provided in Figures 53 through 55. Figure 54 shows that pressures downstream of the emptying valves remain 3.32 m (10.9 ft) below the soffit at the steady state. The 60-percent valve opening also restricts the discharge to 71.7 cms (2,530 cfs). Additional simulations were made to compute the conditions when the emptying valves were raised to the 40-percent open position (Figures 56 through 59) and to the 20-percent open position (Figures 60 through 63).

The results of the partial emptying-valve openings show that this operation is undesirable. The pressures downstream of the emptying valves are close to being too low with the 60-percent valve opening. The minimum cavitation index of 0.63 is marginally acceptable. The 20-percent open position restricts the discharge to only 26.1 cms (920 cfs). The valves (both filling and emptying) should be open 100 percent during the passage of flows for pool lowering.

Full valve openings

The optimization software was programmed to run the LOCKSIM model from initial conditions of an empty lock chamber with filling and emptying valves closed, to the steady-state condition with the valves fully open. The operation constraints were the maximization of the minimum cavitation index below the valves during the establishment of steady flow. A rule was imposed that eliminated the consideration of any valve operations that produced minimum cavitation indexes lower than 0.6. Operation rates of both the filling and the emptying valves and the lag between initiation of the emptying-valve operation were varied. The pool conditions selected for this lock operation optimization was an upper pool el 726.3 and a lower pool el 687.2. The results of these 551 optimization runs are provided on the plots of computed minimum cavitation index downstream of the filling and emptying valves in Figures 64 and 65, respectively. Examination of the runs that reached the steady-state flow condition the fastest and produced the acceptable minimum cavitation indexes for both the filling and the emptying valves indicated that run number 182 was a viable operation scheme. This iteration computed the flow variables using a 591.9-sec filling-valve time, a 160.0-sec emptying-valve time, and a 90.0-sec lag between valve operations. This valve scheme produced

steady-state flow conditions in about 23 min. Timings were rounded to the nearest 0.5 min and resulted in a 10.0-min filling-valve operation time, a 2.5-min emptying-valve opening time, and a 1.5-min lag between initiation of the filling-valve and emptying-valve operations. The results of these simulations are shown in Figures 66 through 69. The steady-state discharge at this head is 93.5 cms (3,305 cfs) and the lock chamber water surface remains at el 703.4. The minimum cavitation index downstream of the filling valves was 1.6 and the minimum cavitation index downstream of the emptying valves was 0.71. This simulation demonstrates an operation schedule that meets the cavitation index guidance for the low tailwater el 687.2.

5 Summary and Conclusions

This evaluation of the Lock 1 filling and emptying system has determined the discharge capacity of the lock system with various valve and pool configurations. Field tests were conducted to answer questions about the ability of the lock to pass flows through the culvert system. Specifically, the field tests determined that both the filling and the emptying valves can be closed when the culverts are flowing and that the accelerations in the intermediate wall are not large for the flow conditions observed. The field data also provided the information needed to validate the numerical model. The LOCKSIM model used the field data to test the model's ability to simulate the hydraulic conditions within the lock filling and emptying system.

Analysis of the field data in conjunction with the numerical model results indicates that steady flow through the lock system is best maintained with both the filling and emptying valves fully opened. Valve operation optimization produced a valve schedule that provided acceptable pressures below the valves while establishing the steady state most rapidly (about 23 min). The operation uses 10-min filling valves, 2.5-min emptying valves, and a 1.5-min lag between initiation of the filling-valve and emptying-valve operations (Figure 66). Although the optimization was conducted for a single lift of 11.9 m (39.1 ft, upper pool el 726.3 and lower pool el 687.2), this is a high lift for this project and the valve schedules are believed to be applicable to other lifts.

It is noted that there is a question as to whether the lowest point on the valve reaches an elevation above the culvert soffit when the valve is at the 100-percent open position. The as-built drawing (Figure 70) of the valve modifications made when the hydraulic cylinder was replaced with the wire rope and winch system show that the crossbeam protrudes into the flow when the valve is fully opened. The field data collection recorded significant movement of the valves when set at the fully opened position with high discharge in the culverts. Also, the field data collection team observed considerable movement of the lift cable and indicated that the flow in the valve well was extremely rough. The water surface was often times below

the culvert soffit elevation. This violent flow condition could introduce vibration loads on the culvert valves during the steady flow passage. Any long-term operation of the valves under these conditions should be avoided. It is recommended that modifications be made to increase the limit settings for the valve openings to raise the valve lifting beam above the elevation of the culvert soffit.

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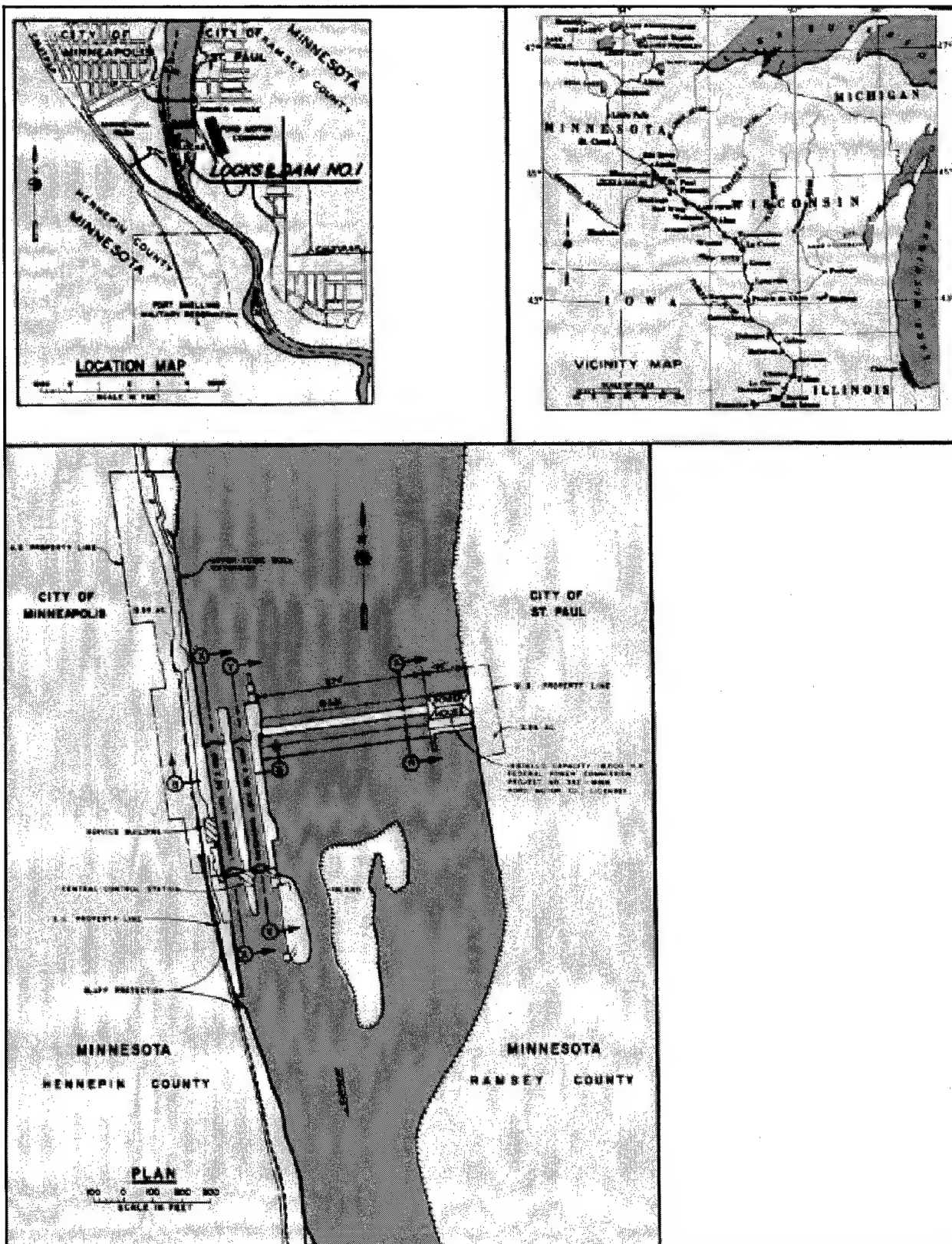
Figure 1.   Location map for Lock and Dam 1, Mississippi River

Figure 2. Plan and profile view of Lock and Dam 1, landward lock
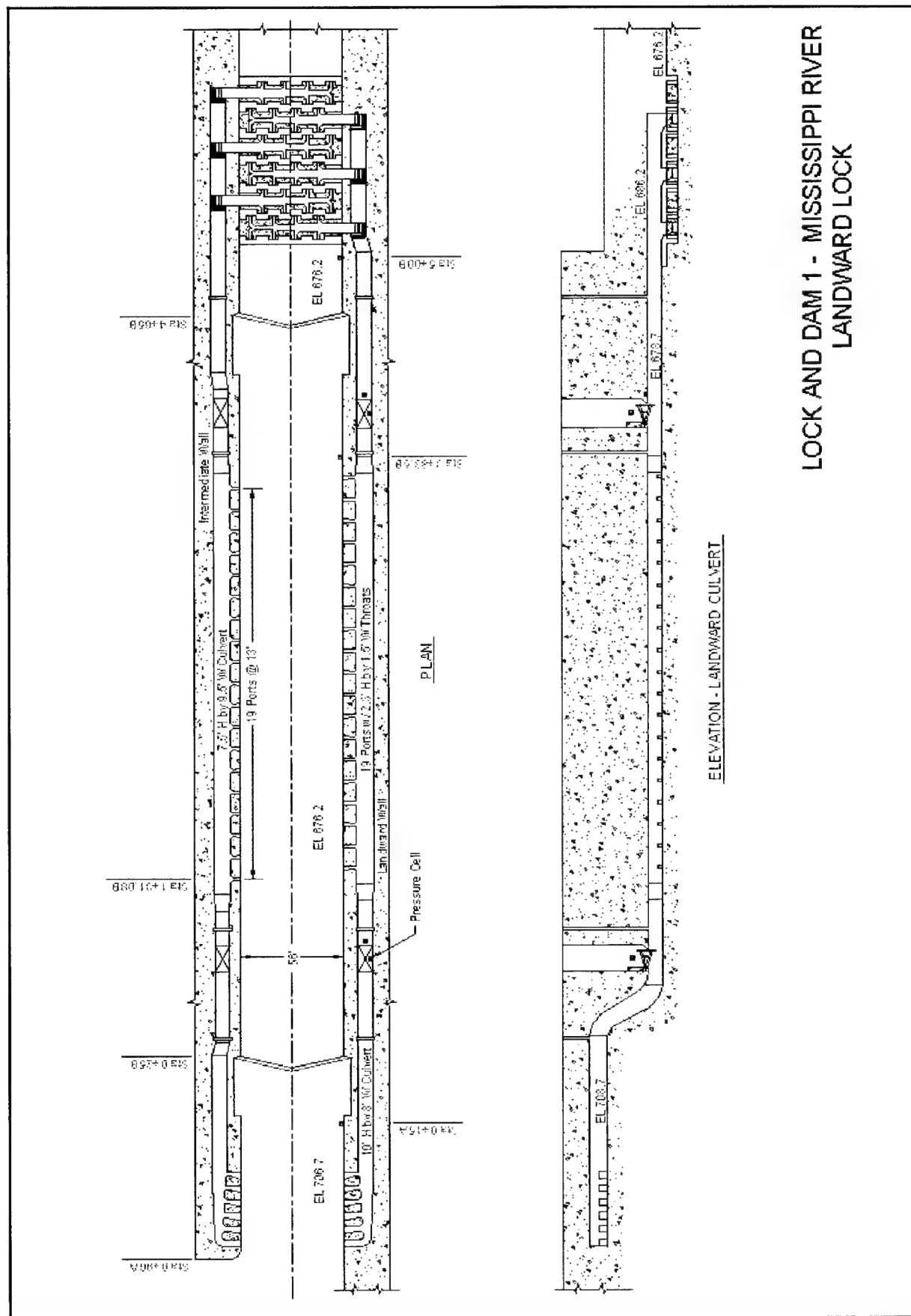
Figure 3. Upper pool water level pressure transducer location

Cables from empty valve well instruments
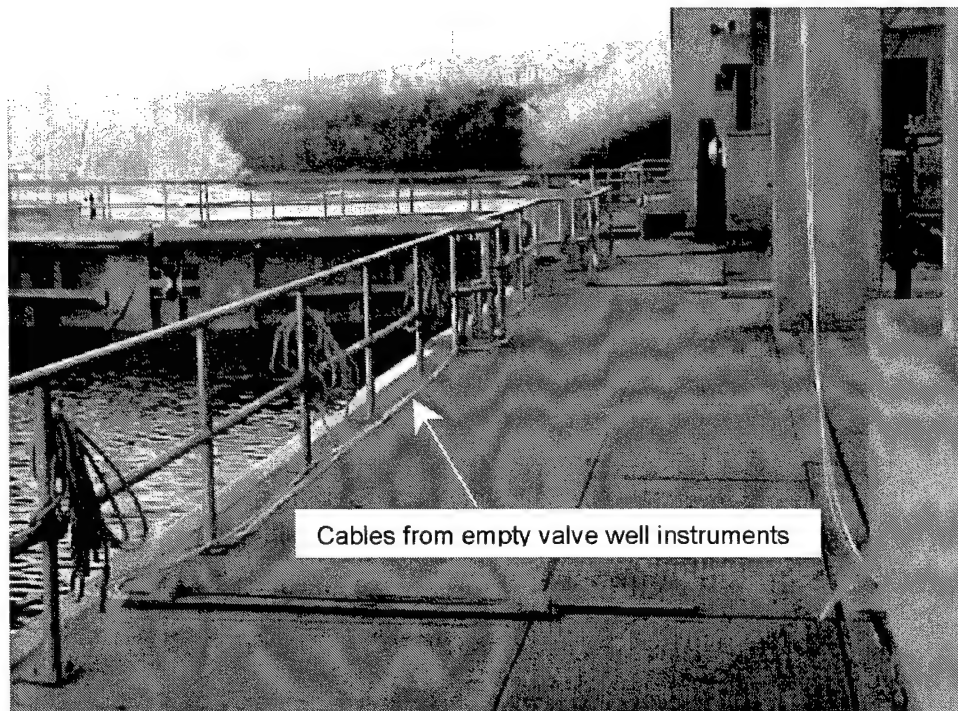
Figure 4. Fill valve well water level pressure transducer

Figure 5.   Lower pool pressure transducer location in the ladder well recess on the land wall

Figure 6.   Data acquisition system location
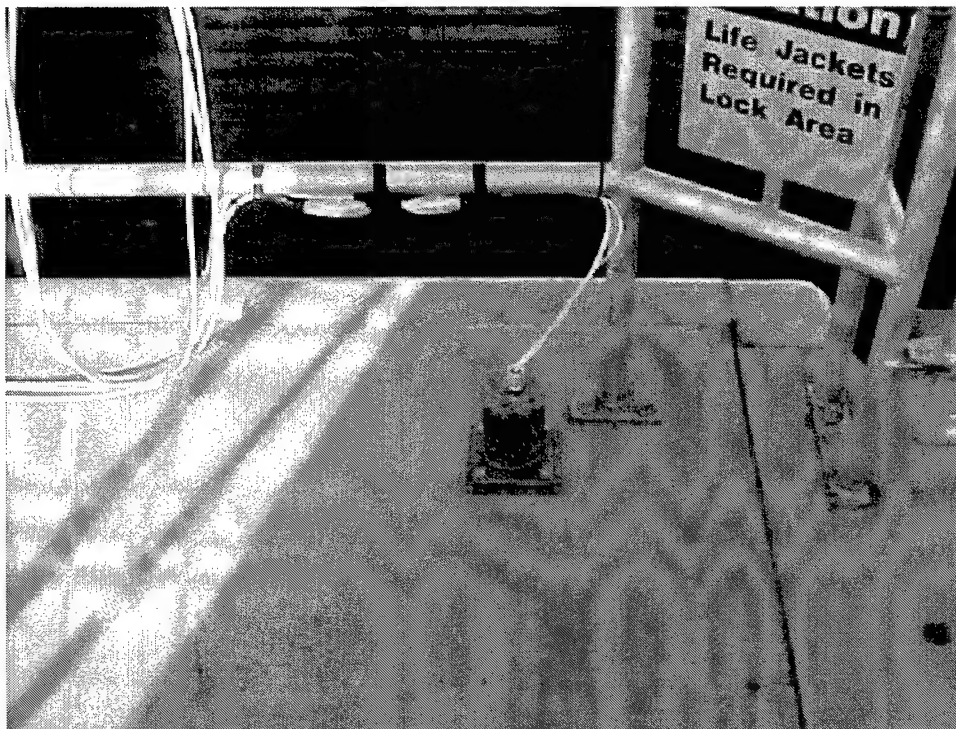
Figure 7.   Triaxial accelerometer mounted on the I-wall

Lock & Dam No. 1
Fill Valve Opening
Dual Valve Lock Fill Operation
3/29/2000
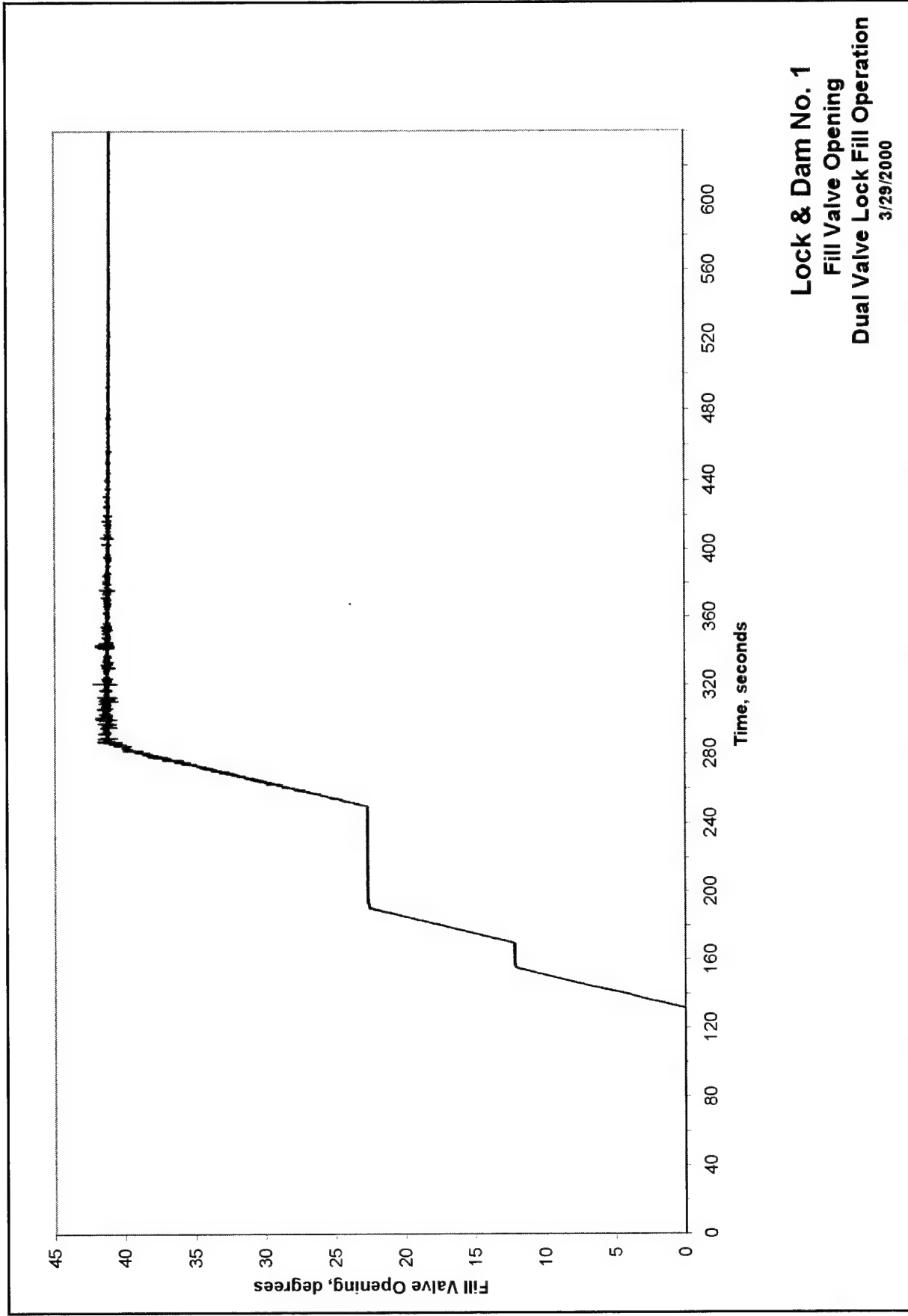
Figure 8. Time-history of sequential fill valve opening

Lock & Dam No. 1
Incremental Fill Valve Opening
Dual Valve Lock Filling Operation
3/29/2000
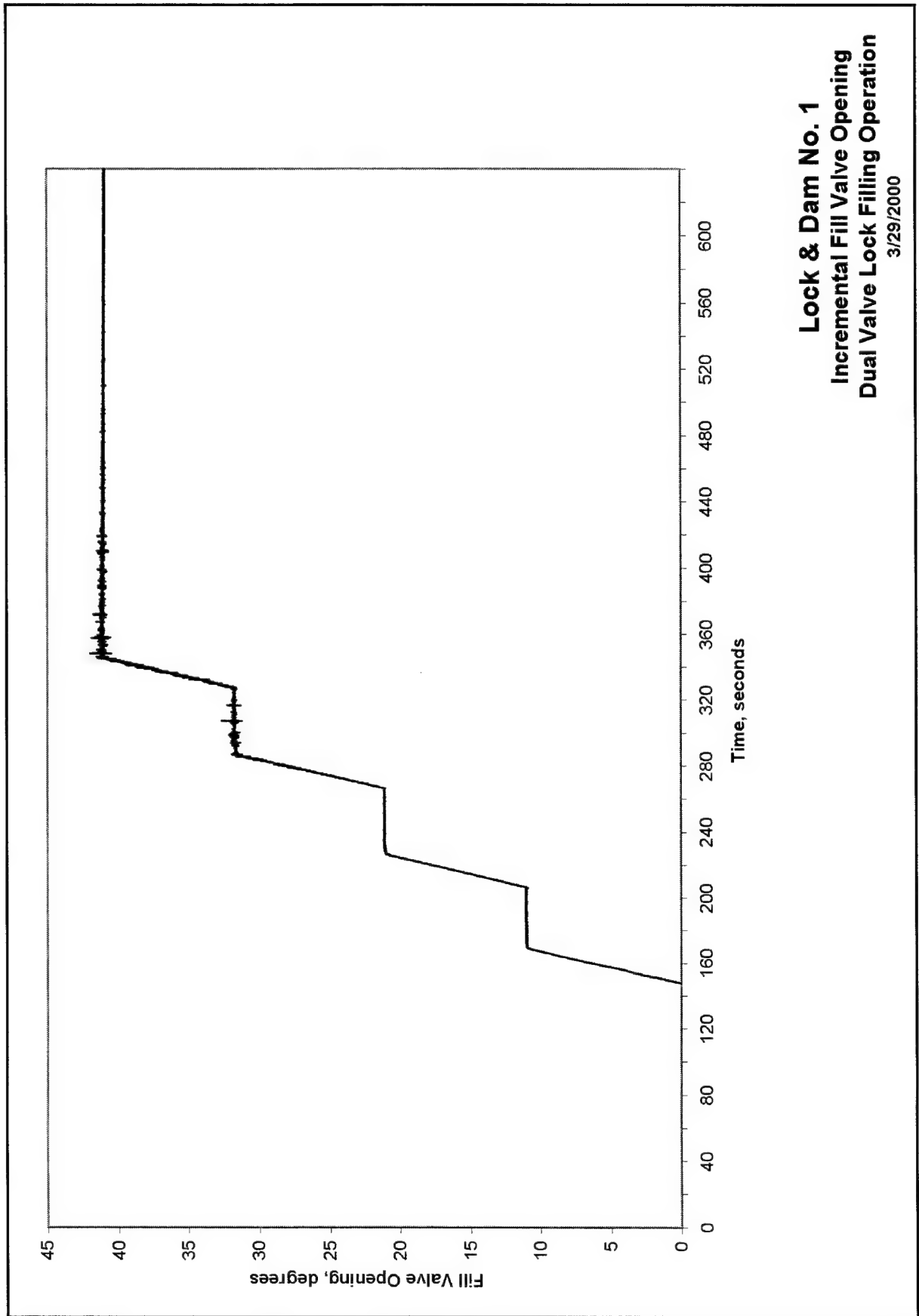
Figure 9. Time-history of incremental fill valve opening during a normal lock filling operation
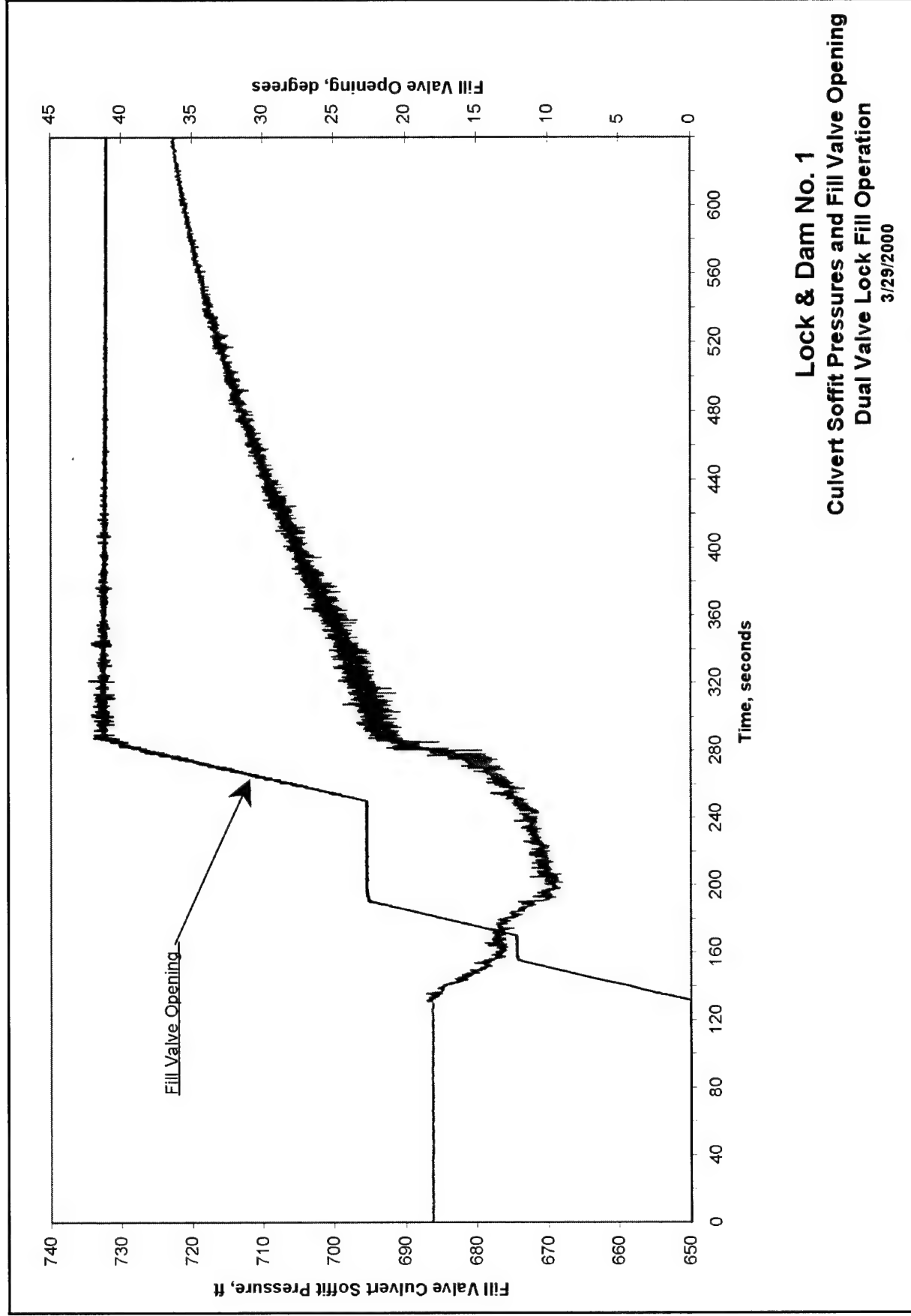
Figure 10. Time-history of fill valve culvert soffit pressures and fill valve opening during a normal lock filling operation. (To convert feet to meters, multiply by 0.3048 (all instances))
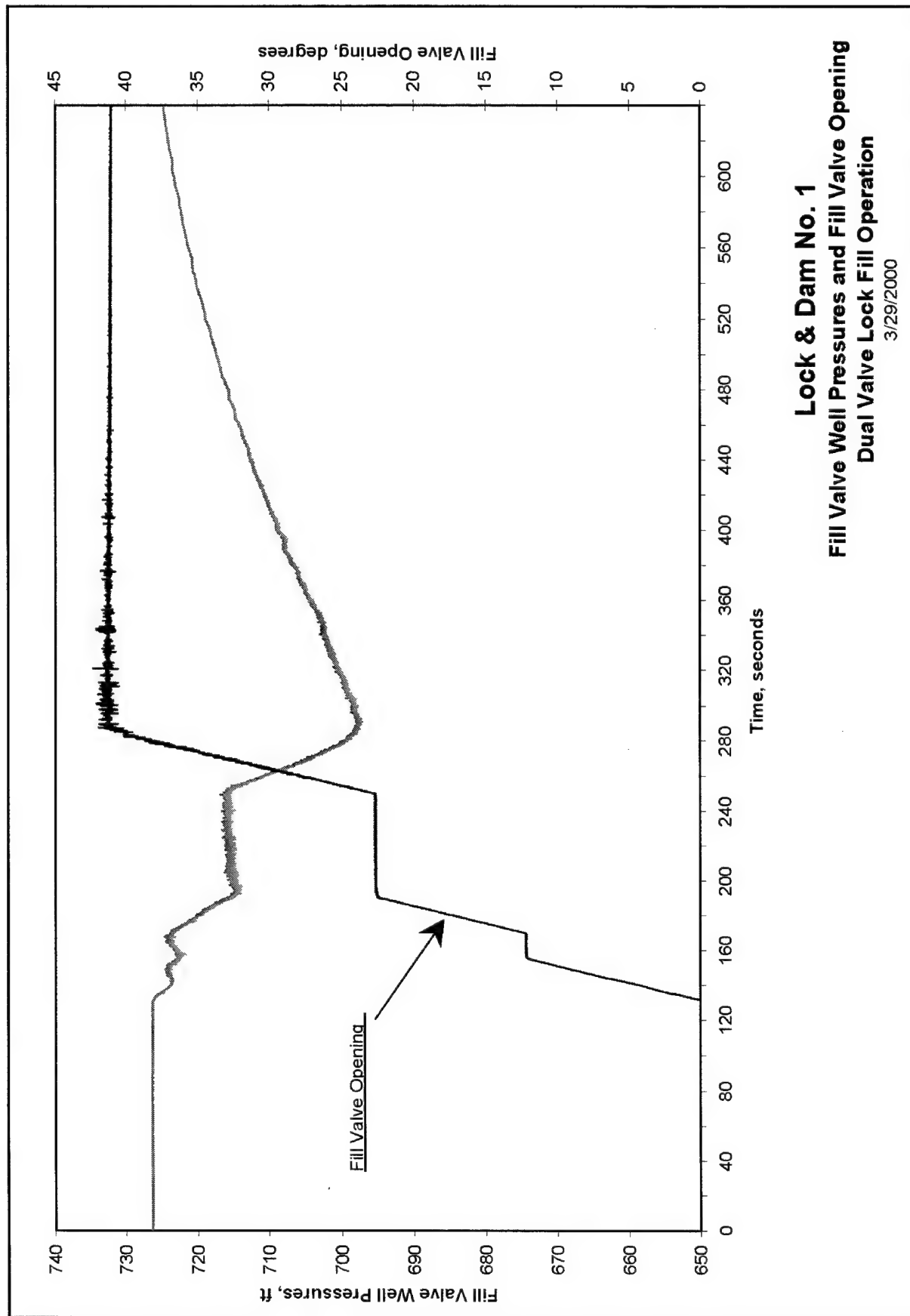
Figure 11. Time-history of fill valve well pressures and fill valve opening during a normal lock filling operation
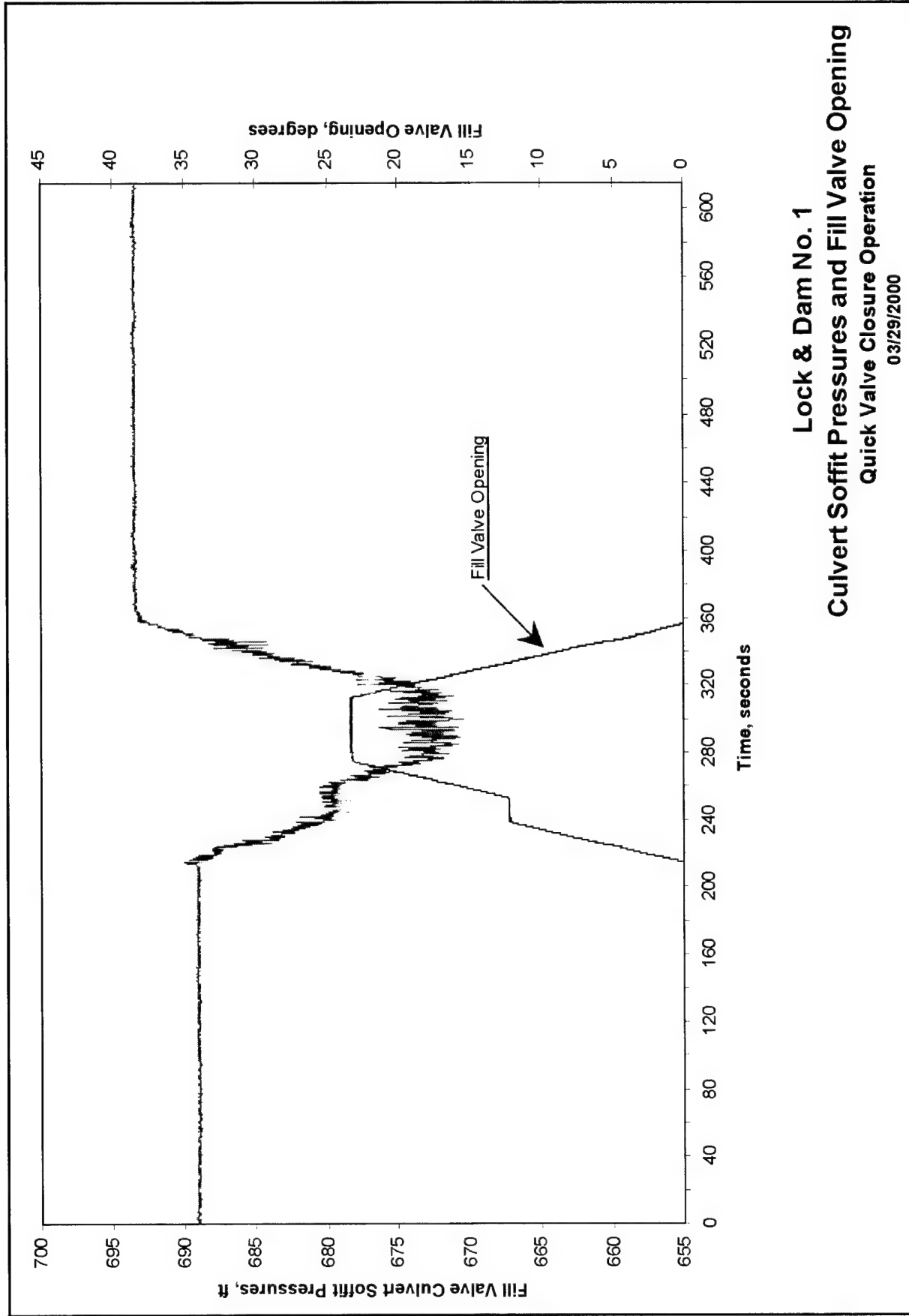
Figure 12. Time-history of fill valve opening and closing during a lock filling operation
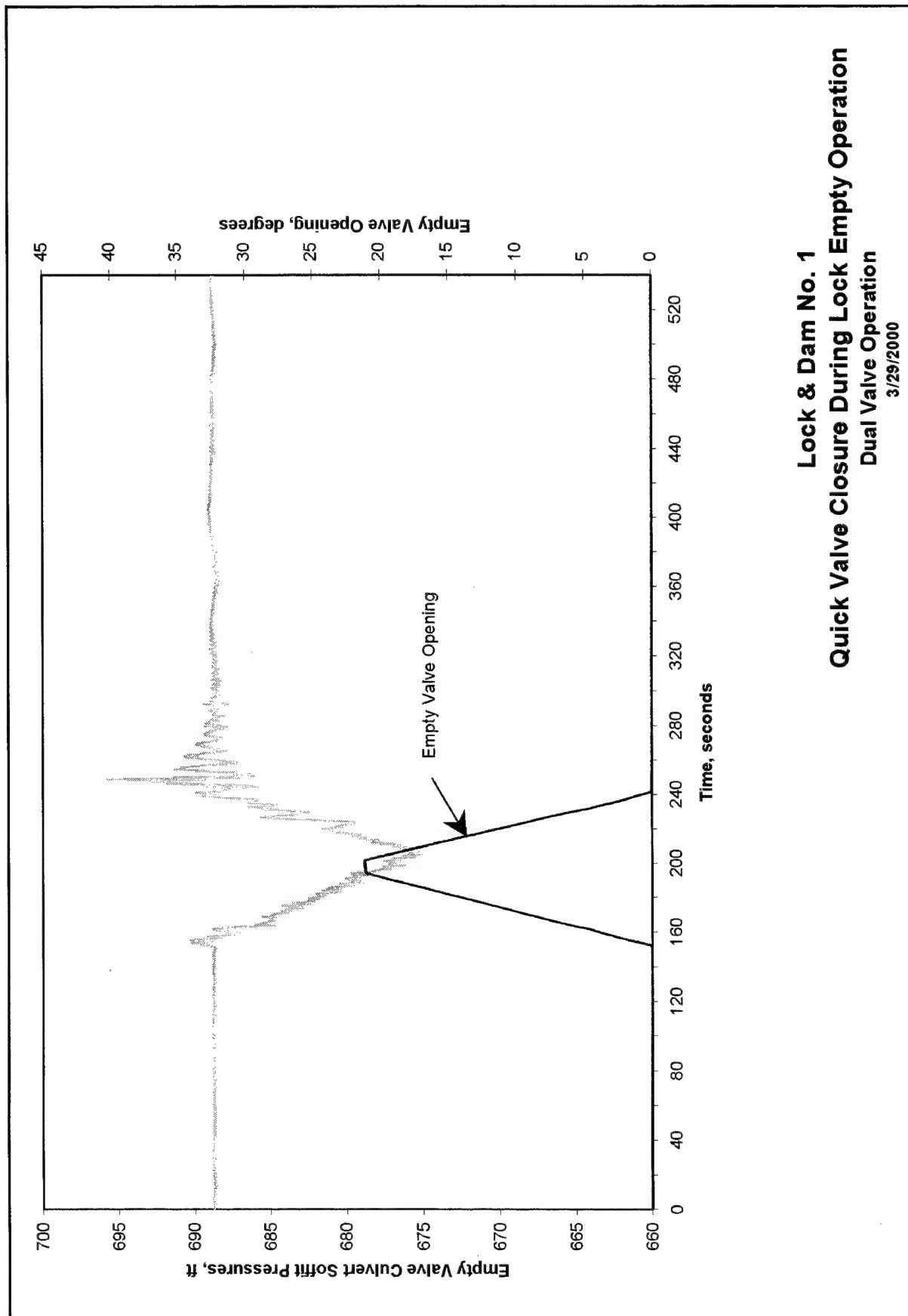
Figure 13. Time-history of empty valve opening and closing to simulate emergency valve closing during a lock empty operation
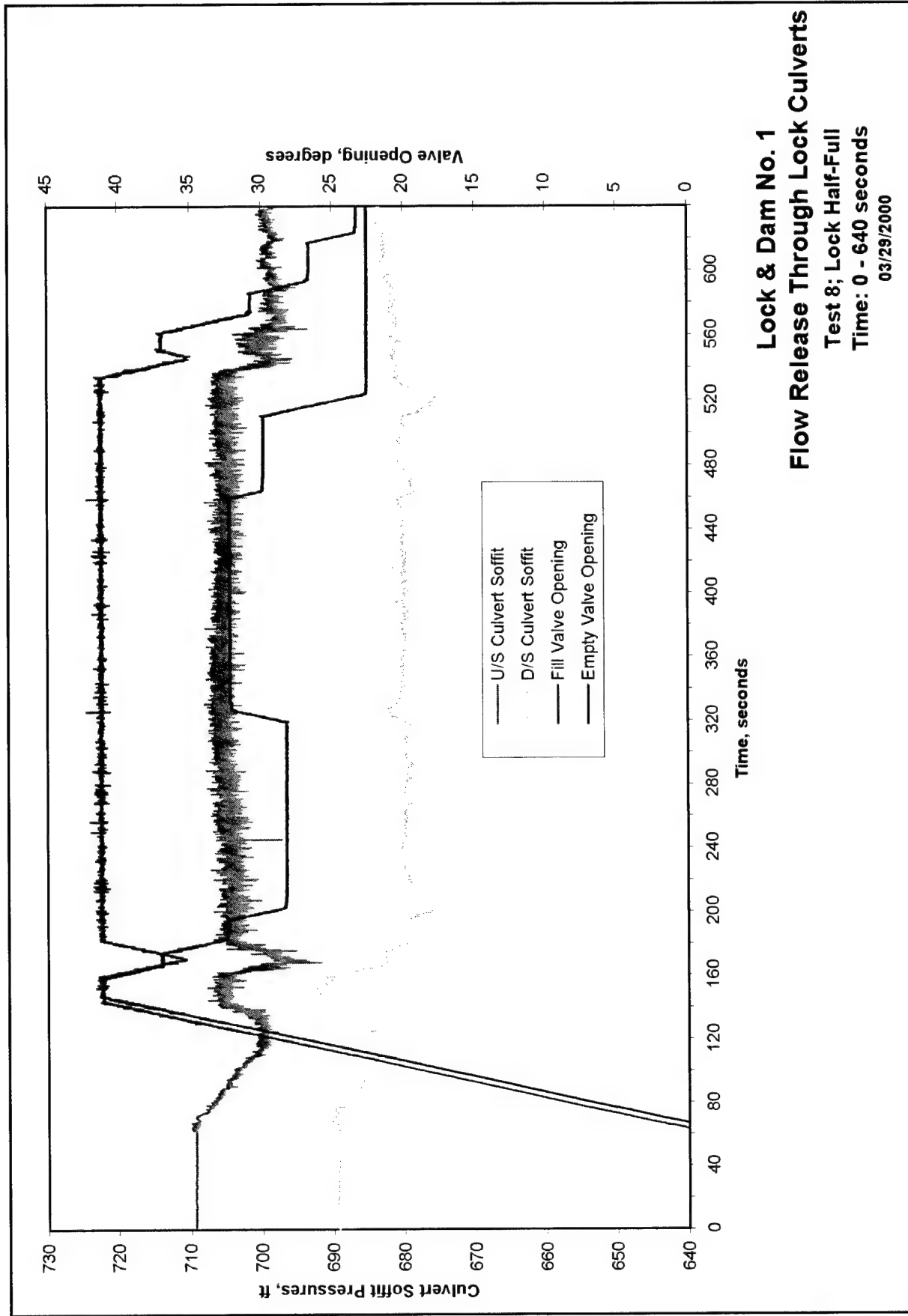
Figure 14. Time-history of culvert soffit pressures anf valve openings for flow releases through the lock culverts; time: 0 to 640 sec
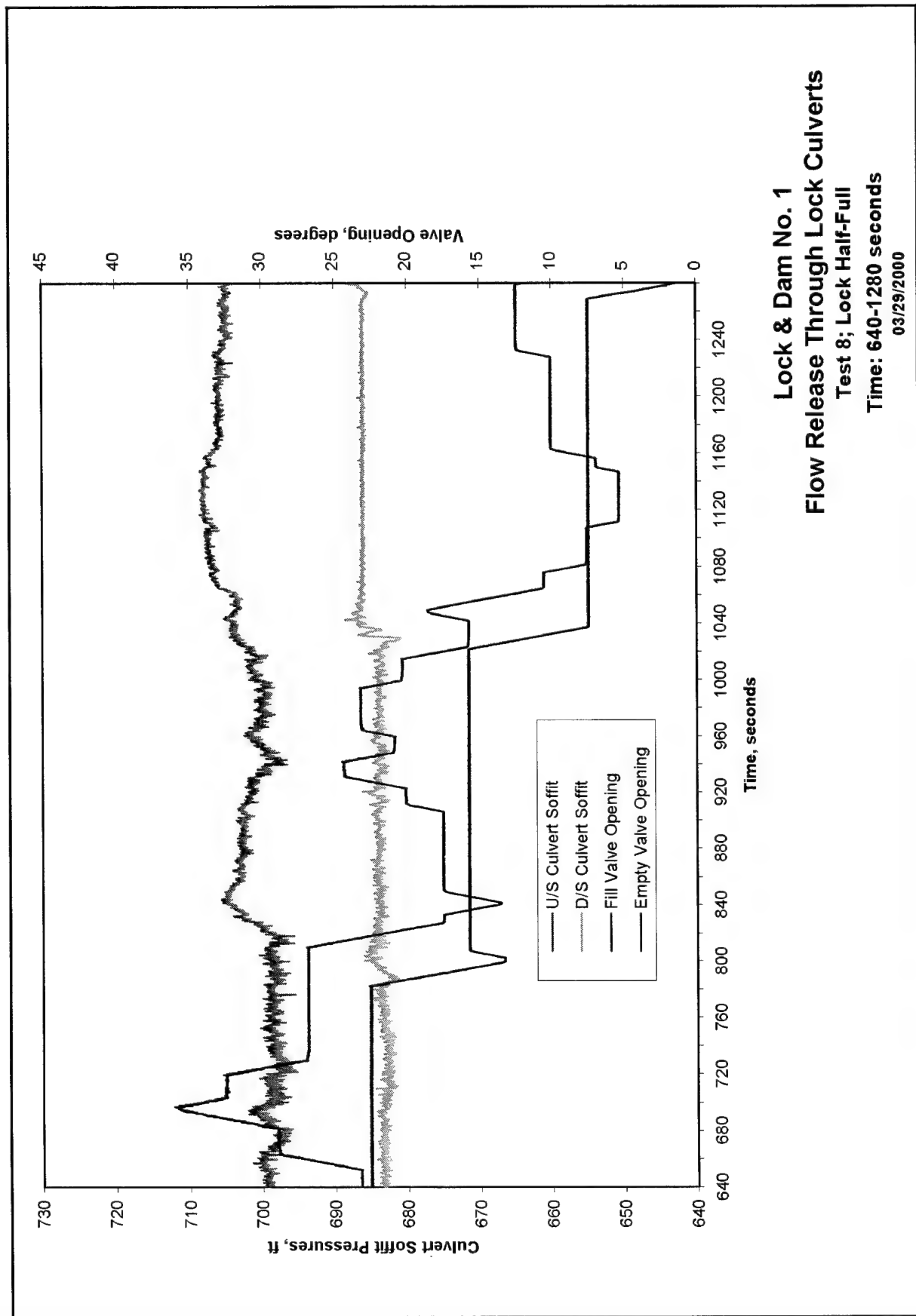
Figure 15. Time-history of culvert soffit pressures and valve openings for flow releases through the lock culverts; time: 640 to 1,280 sec
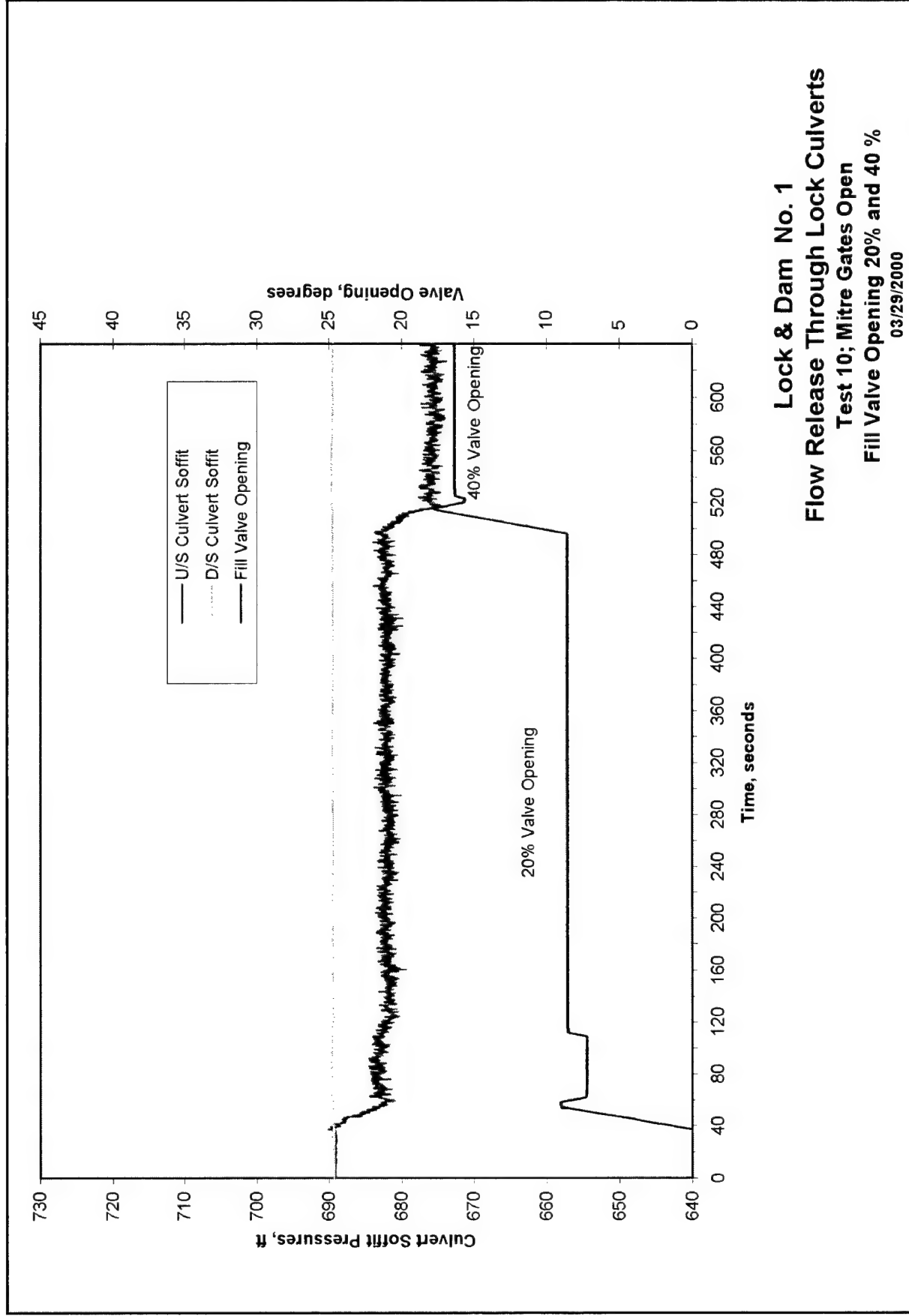
Figure 16. Time-history of culvert soffit pressures and valve openings for flow releases through lock culverts with the lower miter gates open
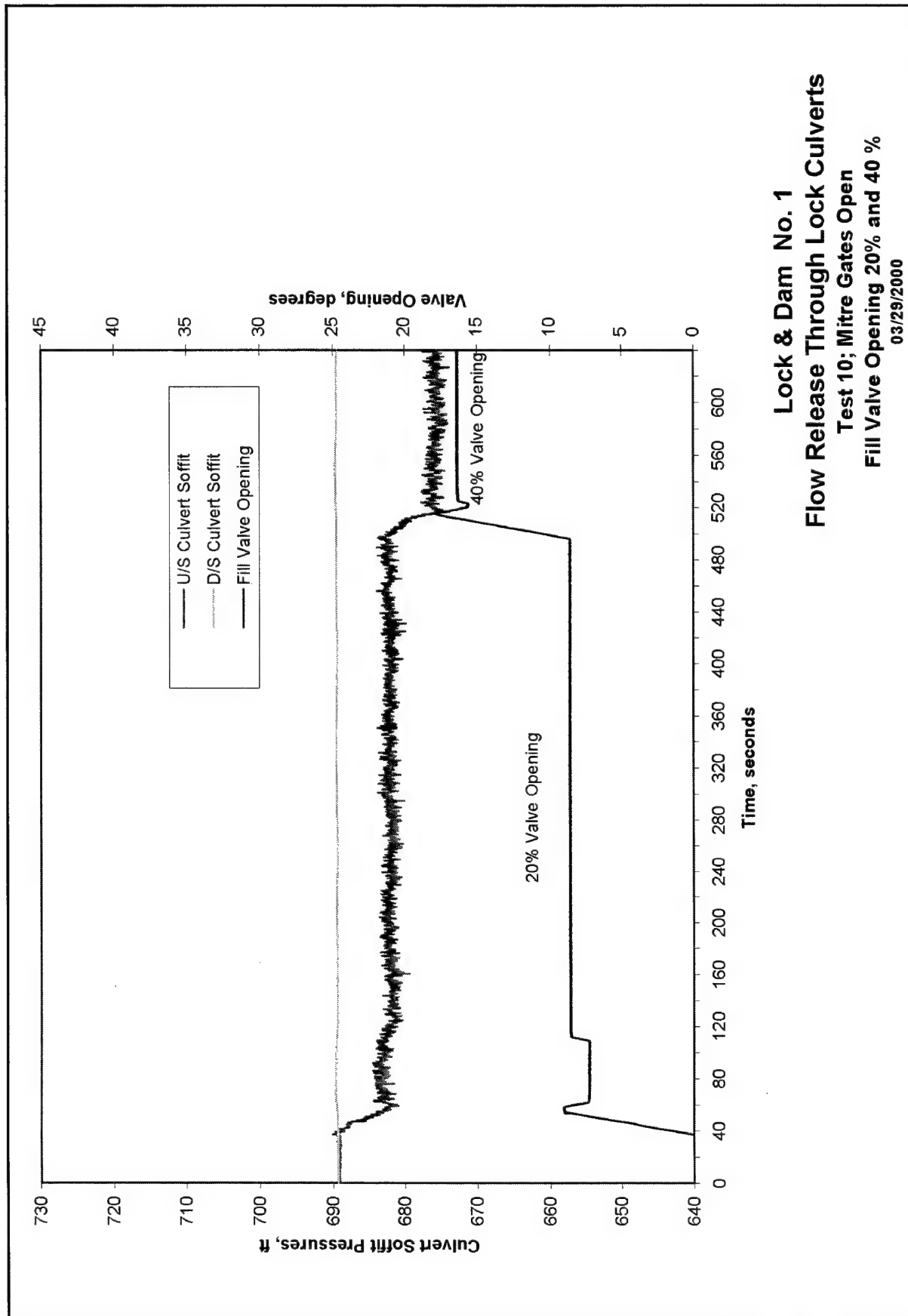
Figure 17. Time-history of culvert pressures, lock chamber water surface, and valve opening for flow release operation; time: 0 to 520 sec
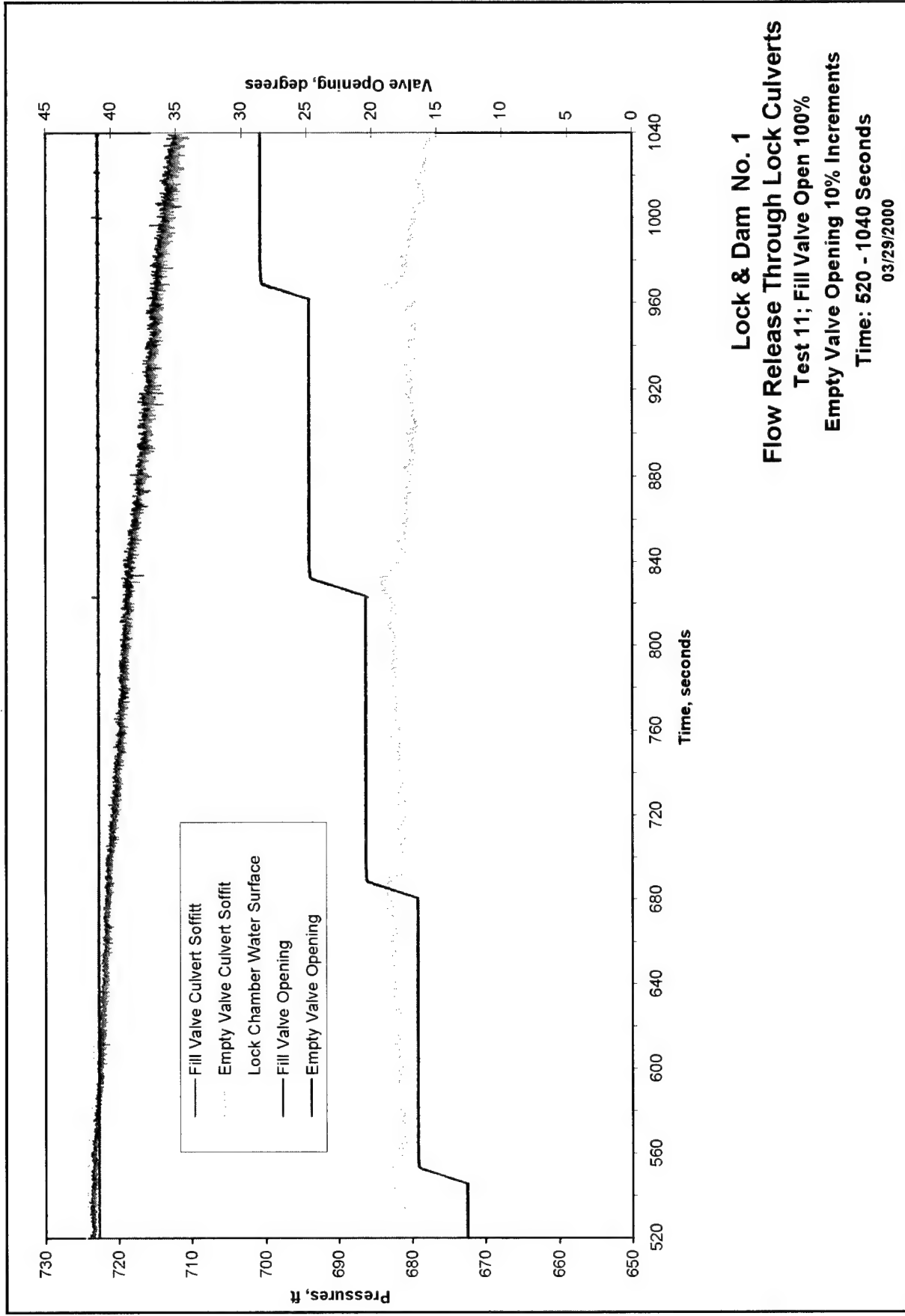
Figure 18. Time-history of culvert pressures, lock chamber water surface, and valve opening for flow release operation; time: 520 to 1,040 sec
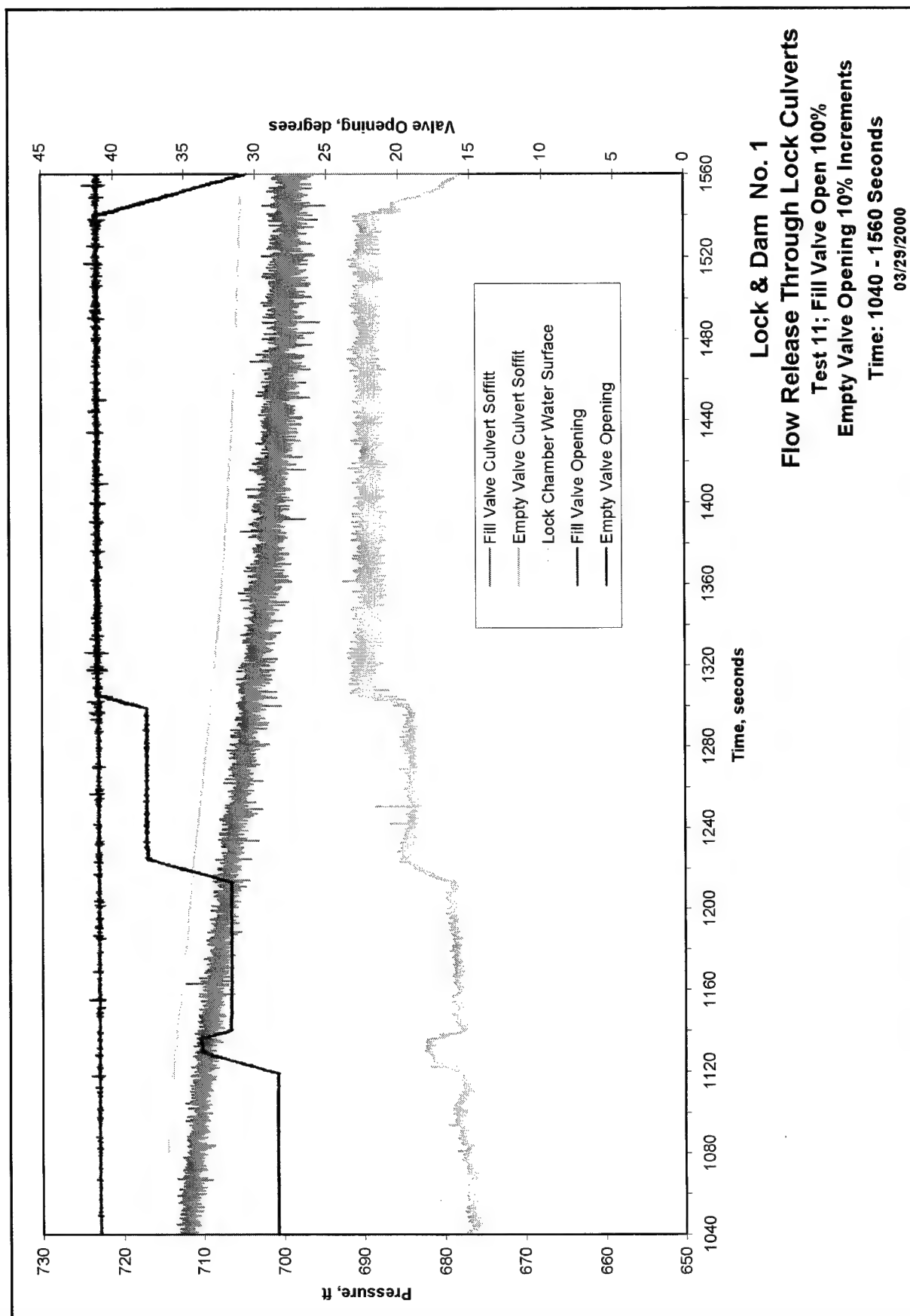
Figure 19. Time-history of culvert pressures, lock chamber water surface, and valve opening for flow release operation; time: 1,040 to 1,560 sec
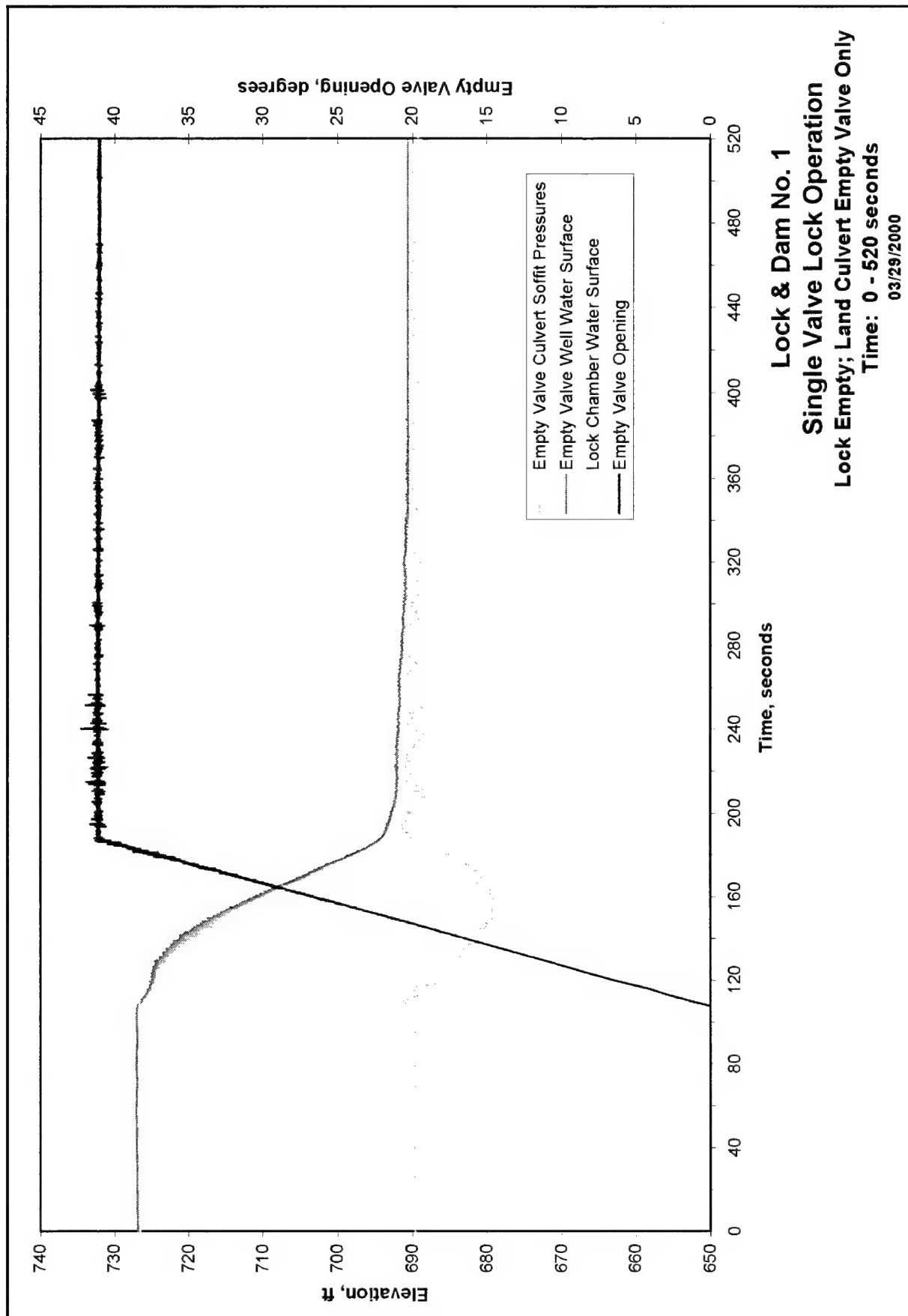
Figure 20. Time-history of culvert pressures, lock chamber water surface, empty valve well water surface, and empty valve opening for a single valve lock empty operation; time: 0 to 520 sec
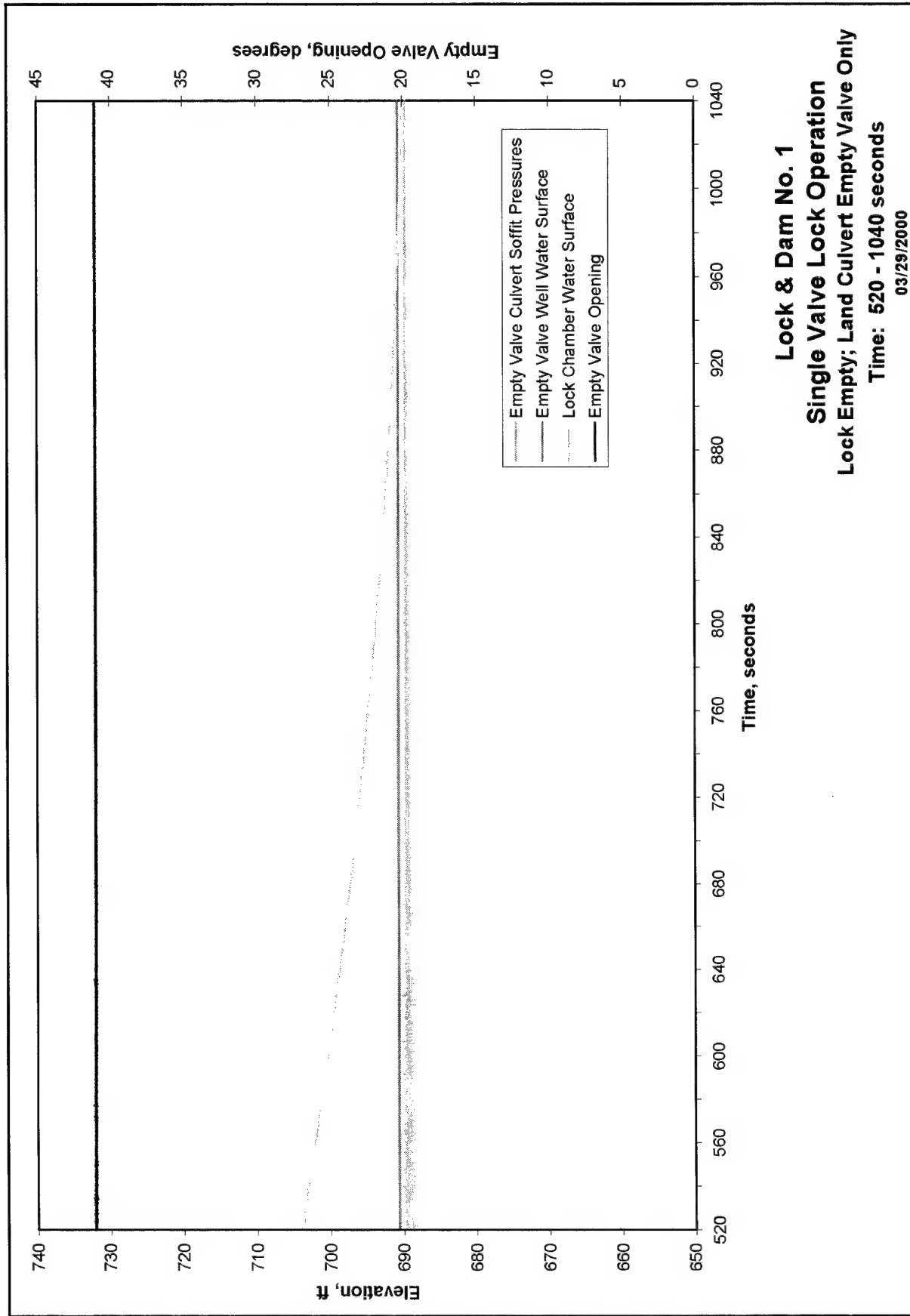
Figure 21. Time-history of culvert pressures, empty valve well water surface, lock chamber water surface, and empty valve opening for a single valve lock emptying operation; time: 520 to 1,040 sec
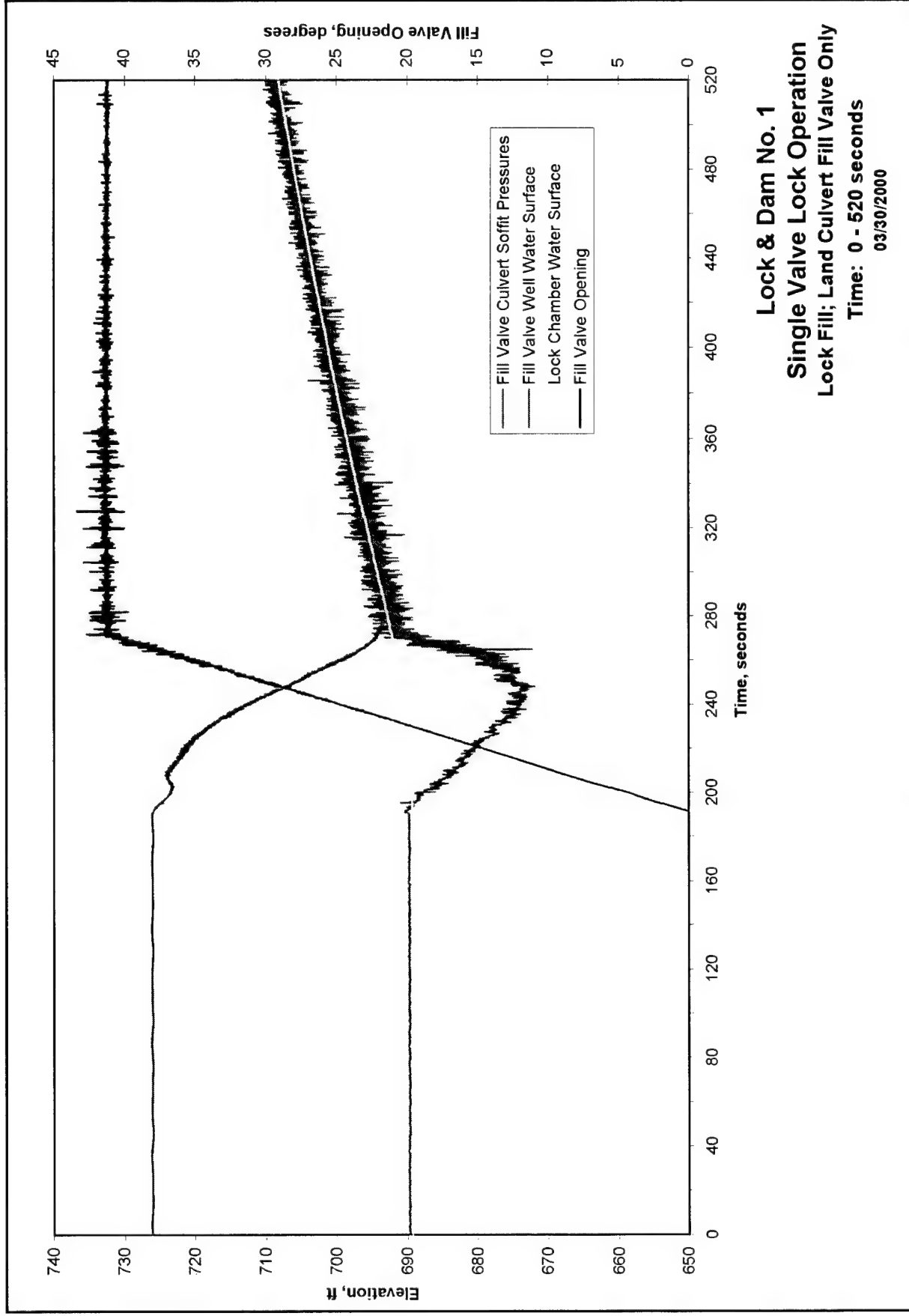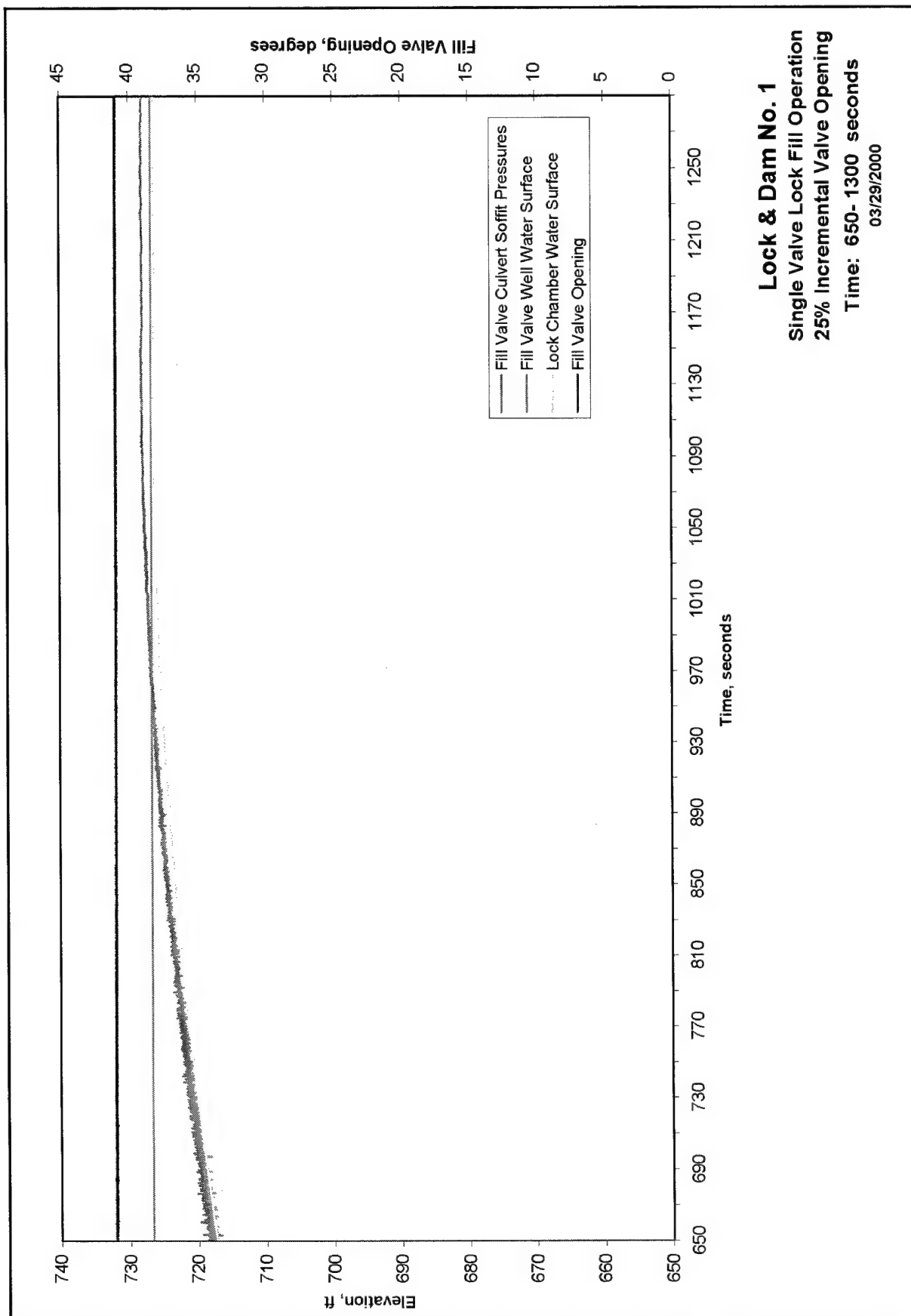
Figure 22. Time-history of culvert pressures, fill valve well water surface, lock chamber water surface, and fill valve opening for a single valve lock filling operation; time: 0 to 520 sec
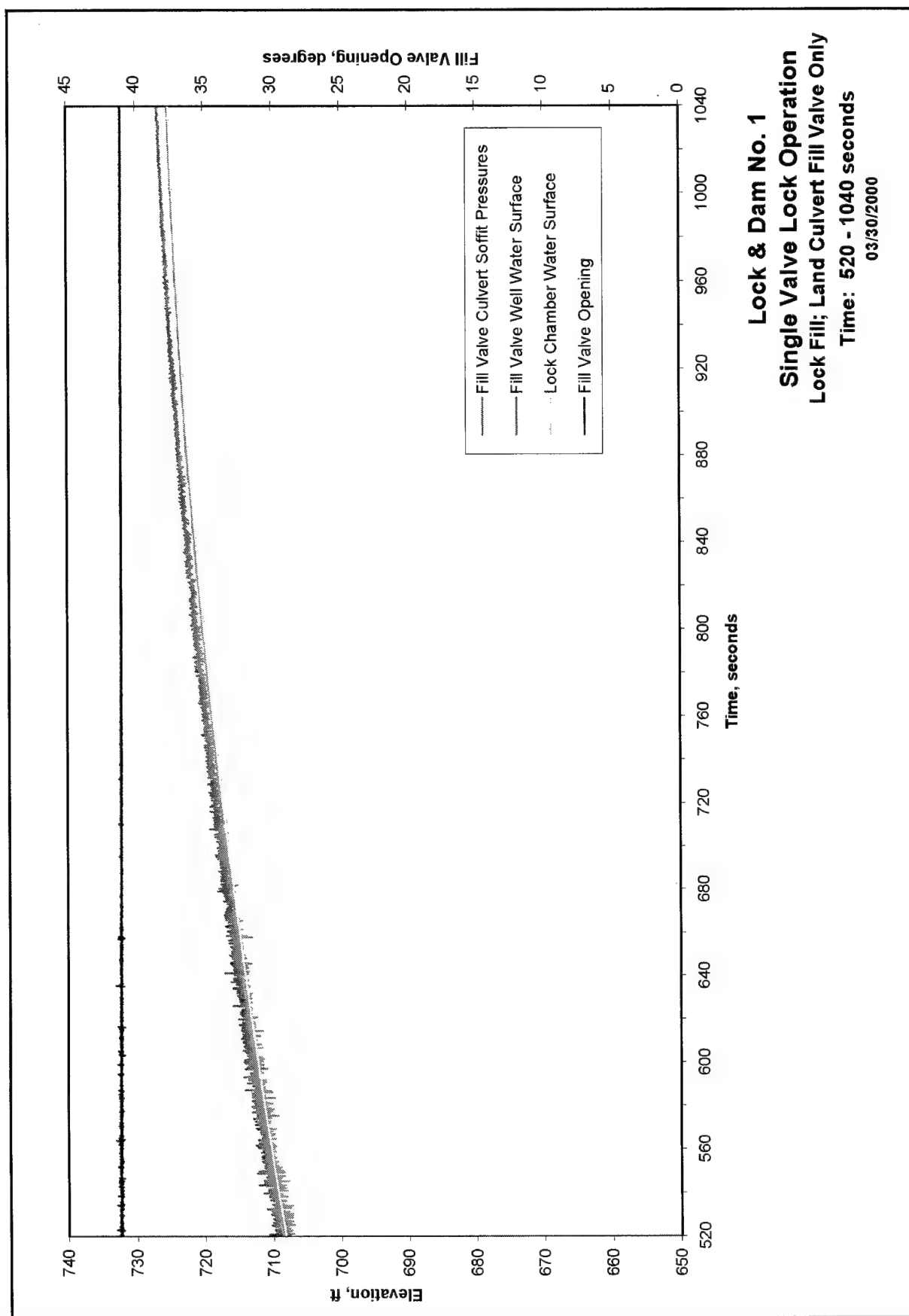
Figure 23. Time-history of culvert pressures, fill valve well water surface, lock chamber water surface, and fill valve opening for a single valve lock filling operation; time: 520 to 1,040 sec
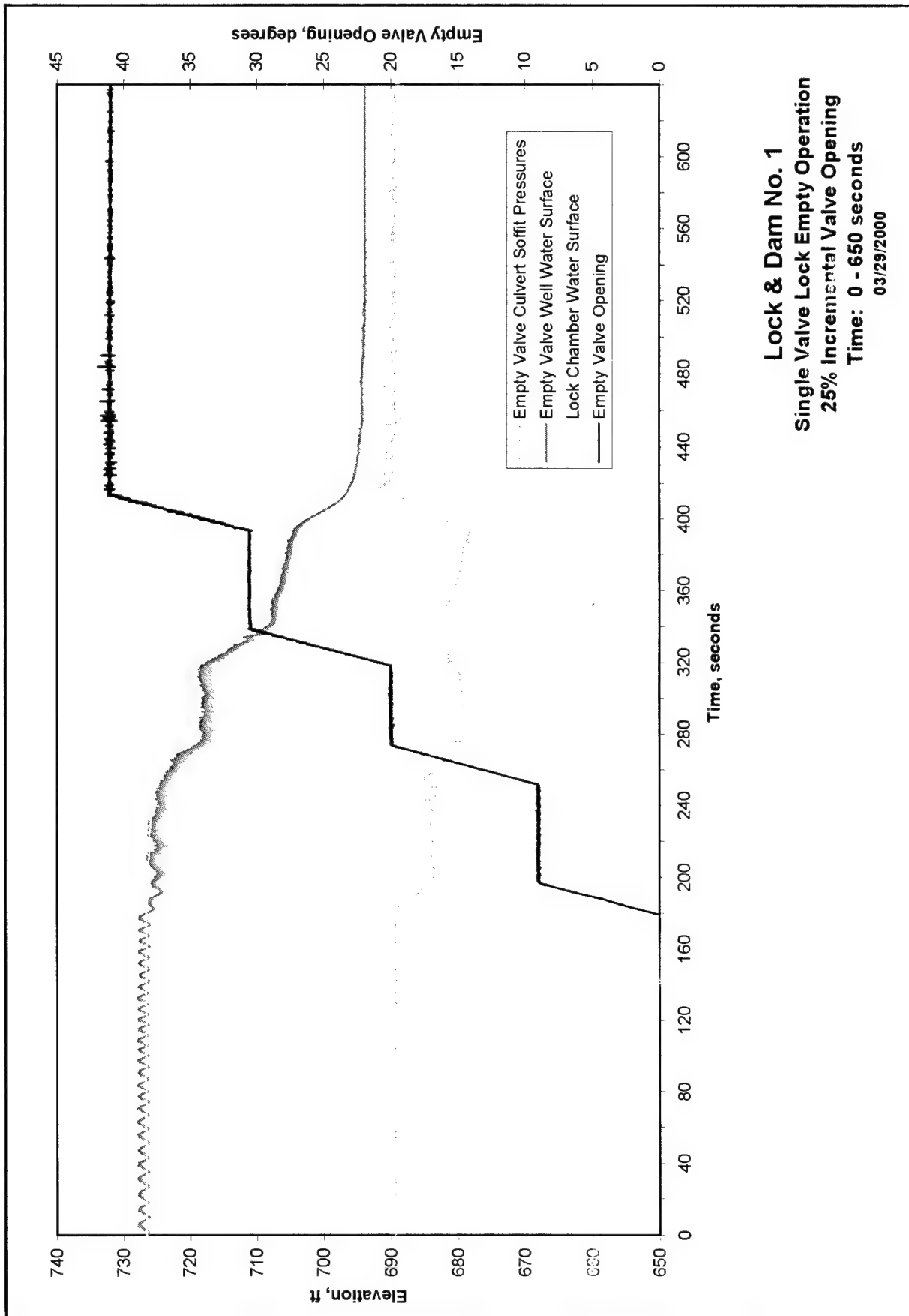
Figure 24. Time-history of culvert pressure, empty valve well water surface, lock chamber water surface, and empty valve openings for a single valve lock empty operation with incremental valve opening; time: 0 to 650 sec
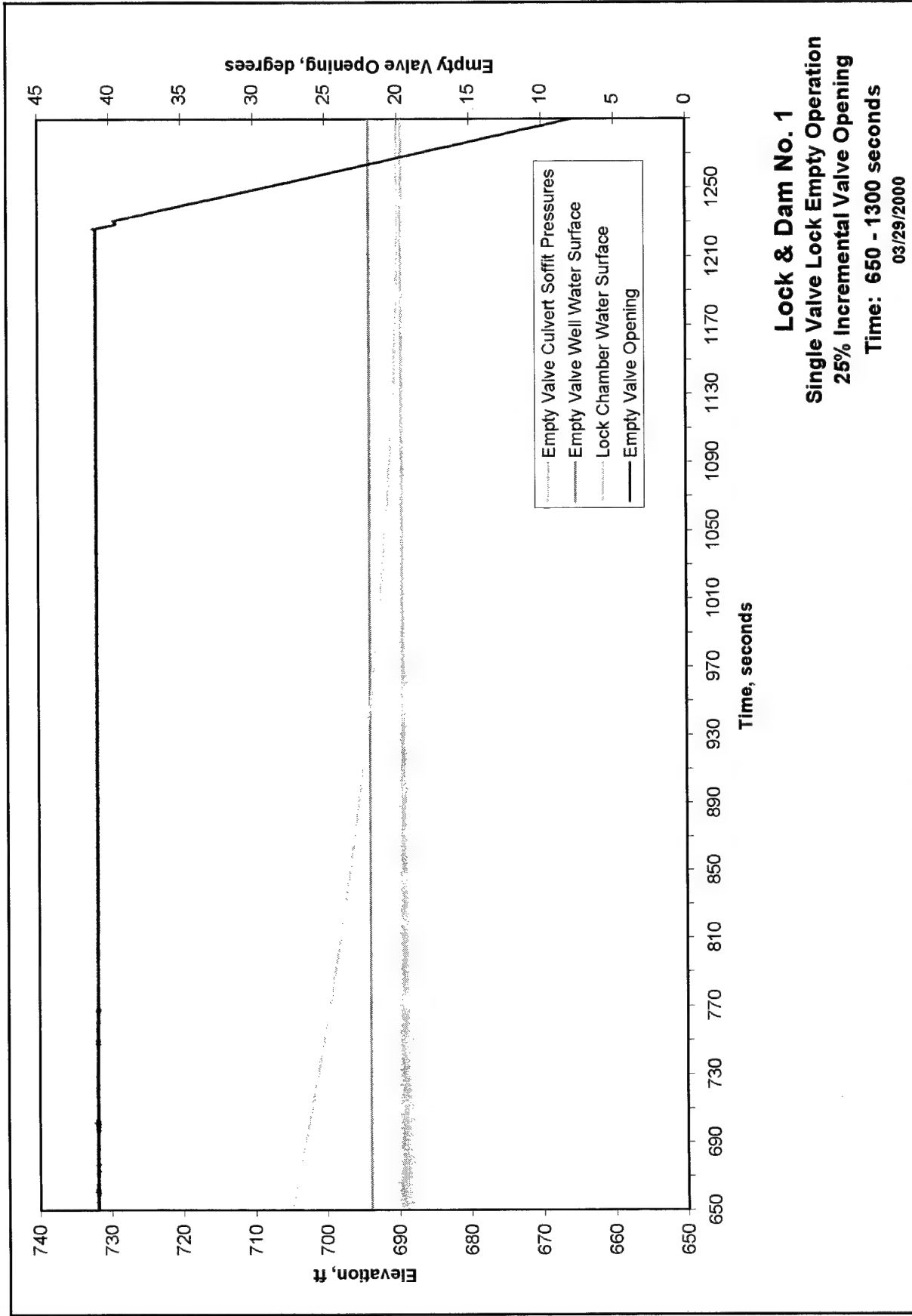
Figure 25. Time-history of culvert pressure, empty valve well water surface, lock chamber water surface, and empty valve opening for a lock empty operation with incremental valve opening; time: 650 to 1,300 sec
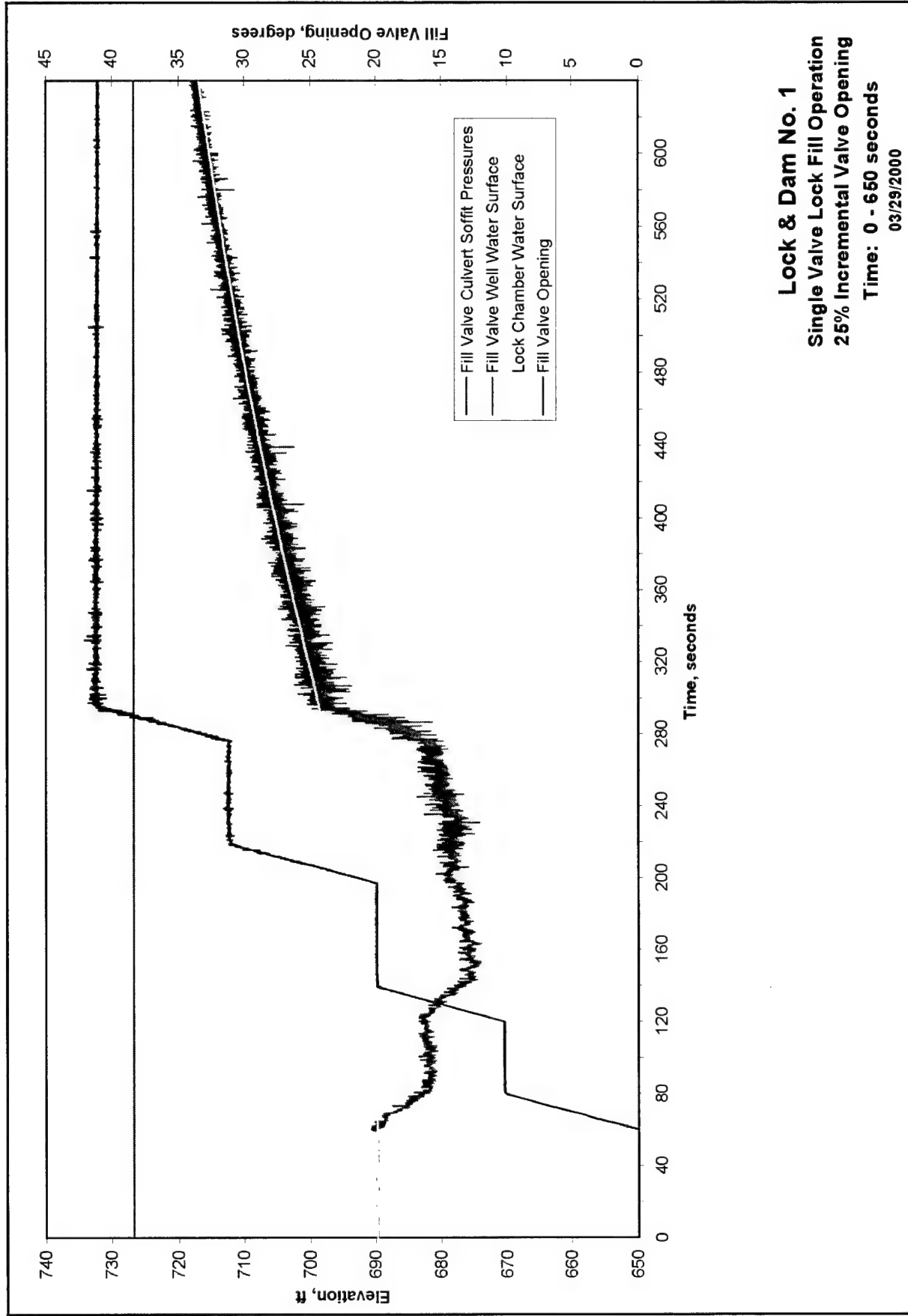
Figure 26. Time-history of culvert pressure, fill valve well water surface, lock chamber water surface, and fill valve opening for a single valve lock filling operation with incremental valve opening; time: 0 to 650 sec

Figure 27. Time-history of culvert pressure, fill valve well water surface, lock chamber water surface, and fill valve opening for a single valve lock filling operation with incremental valve opening; time: 650 to 1,300 sec
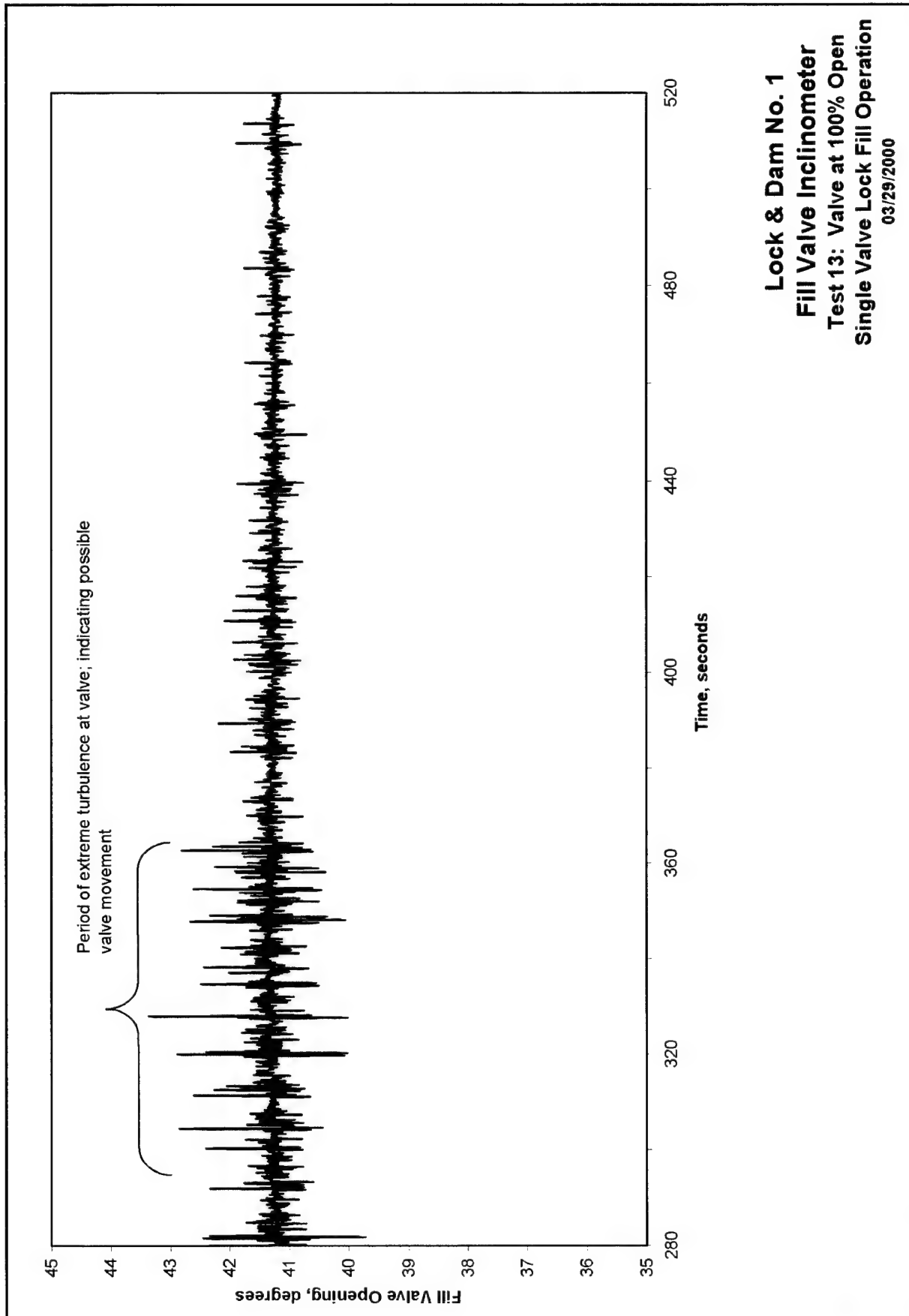
Figure 28. Time-history of fill valve inclinometer indicating possible valve movement during periods of extreme turbulence in the valve well area
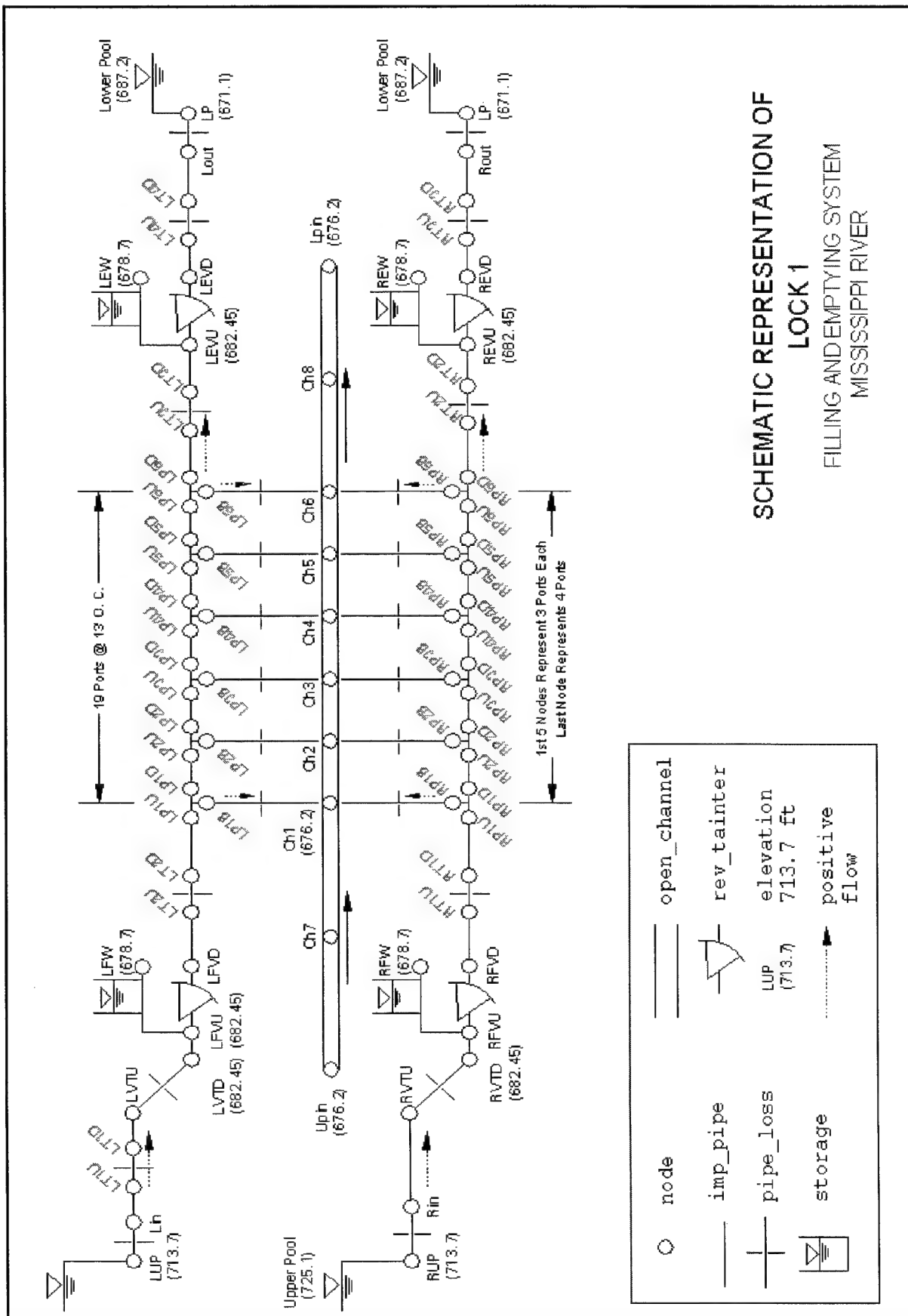
Figure 29. Schematic of LOCKSIM model
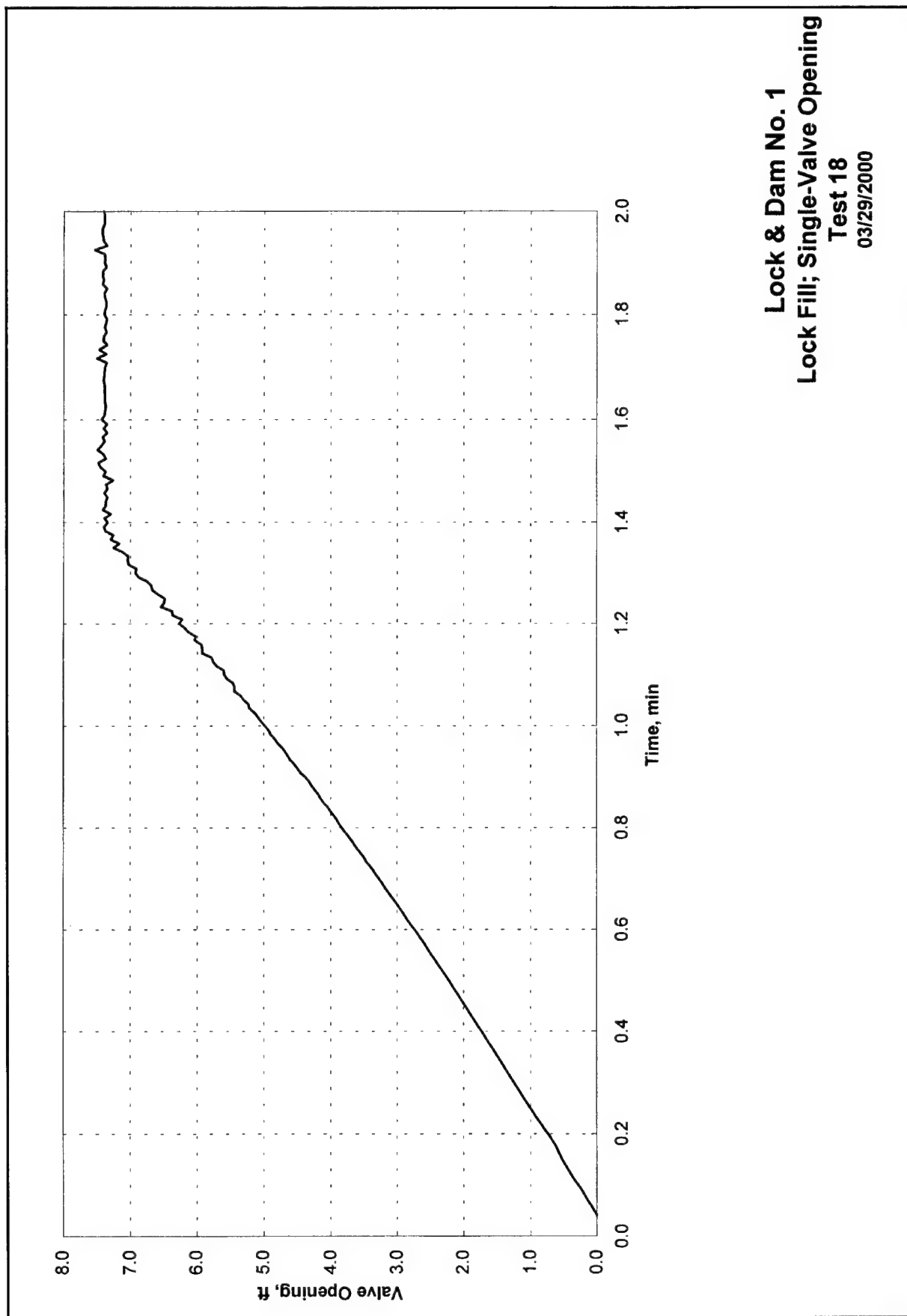
Figure 30. Valve schedule for single-valve lock filling operation (Test 18)
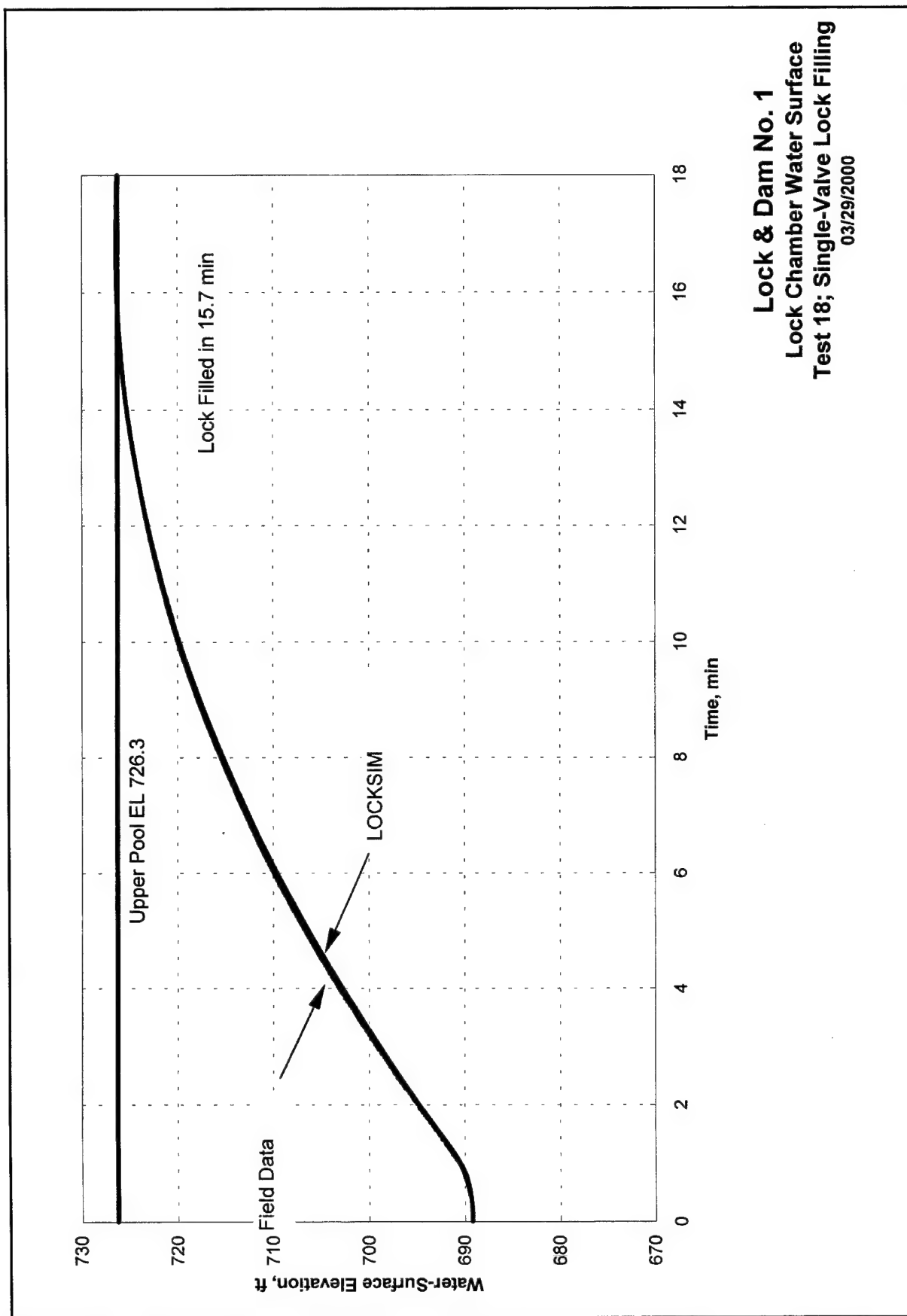
Figure 31. Lock chamber water surface, Test 18 – single-valve filling operation, upper pool el 726.3, lower pool el 689.2

Lock & Dam No. 1
Fill-Valve Well Water Surface
Test 18; Single-Valve Lock Filling
03/29/2000
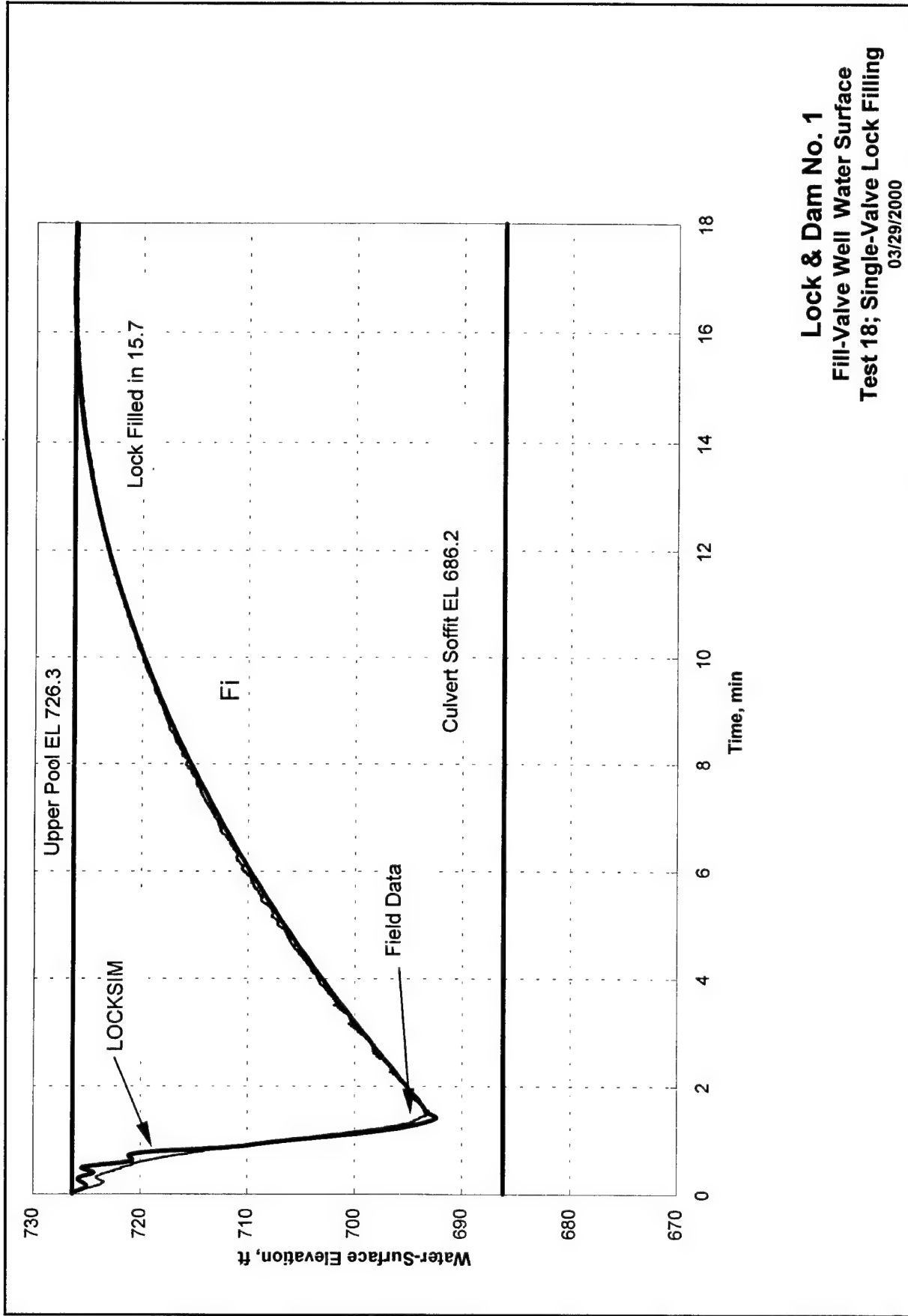
Figure 32. Water surface in fill-valve well, Test 18 – single-valve filling operation, upper pool el 726.3, lower pool el 689.2
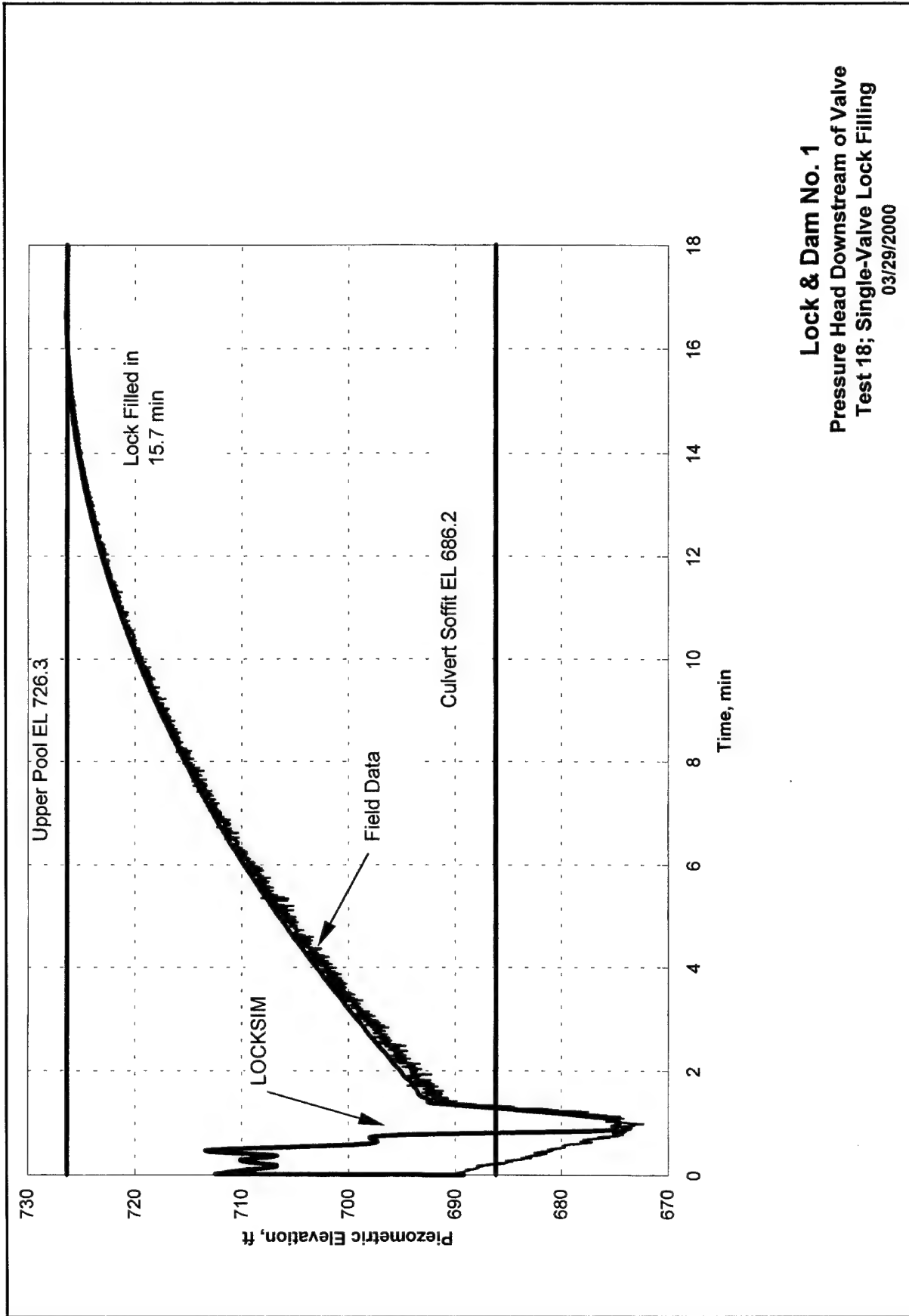
Figure 33. Pressure head downstream of fill valve, Test 18 – single-valve filling operation, upper pool el 726.3, lower pool el 689.2
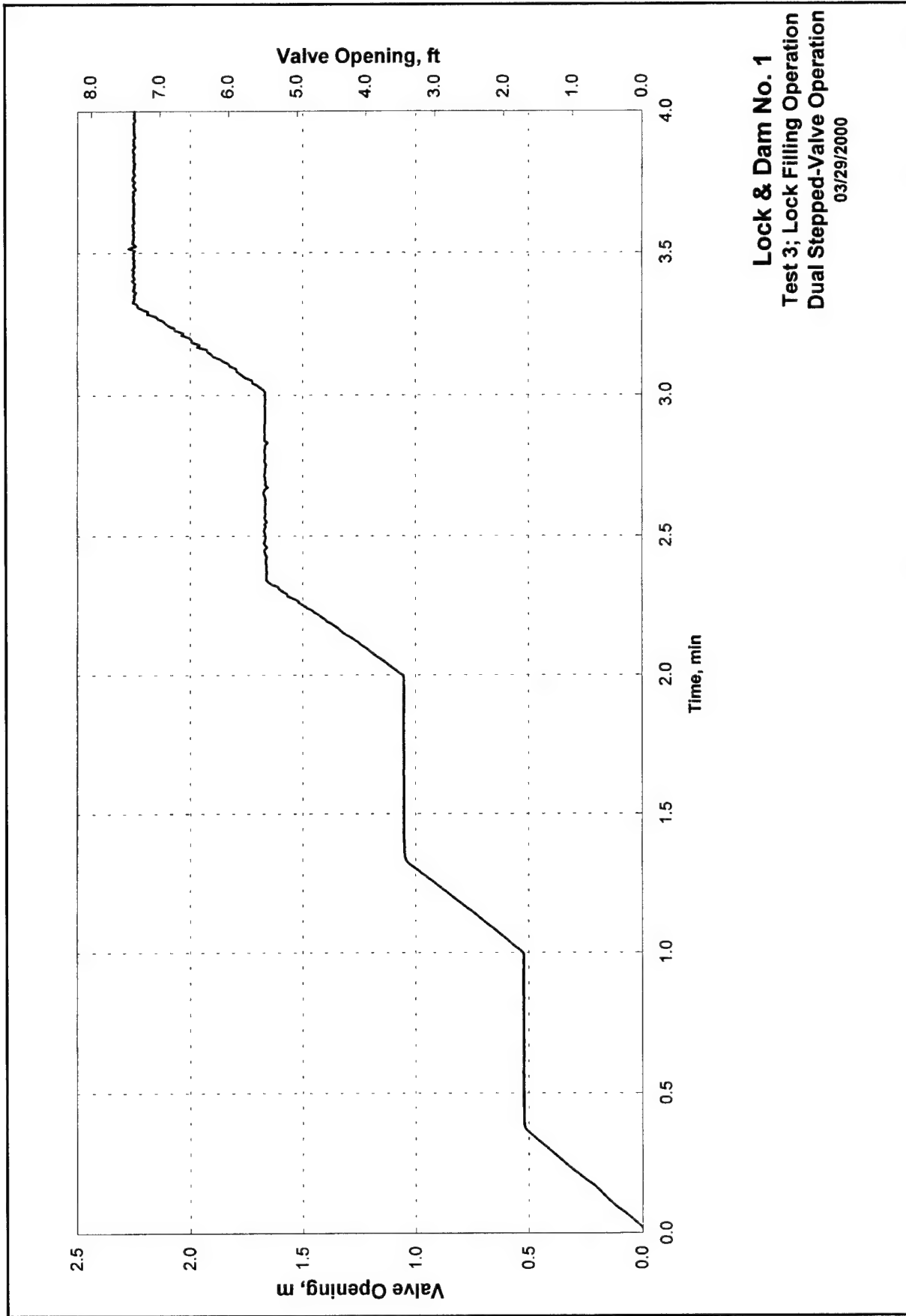
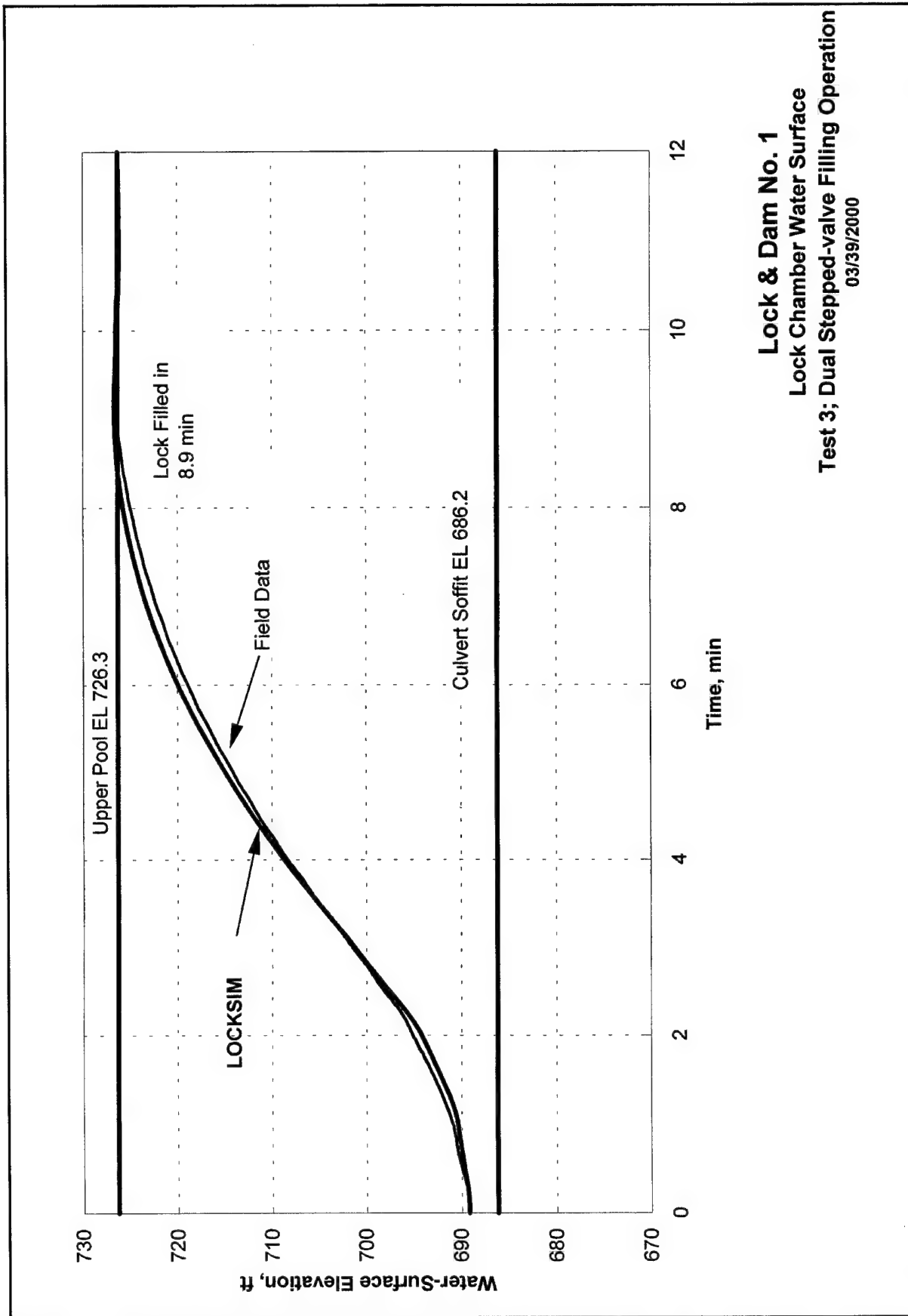Figure 34. Test 3 valve operation schedule, dual stepped-valve operation

Figure 35. Lock chamber water surface, Test 3 – dual stepped-valve filling operation, upper pool el 726.3, lower pool el 689.2
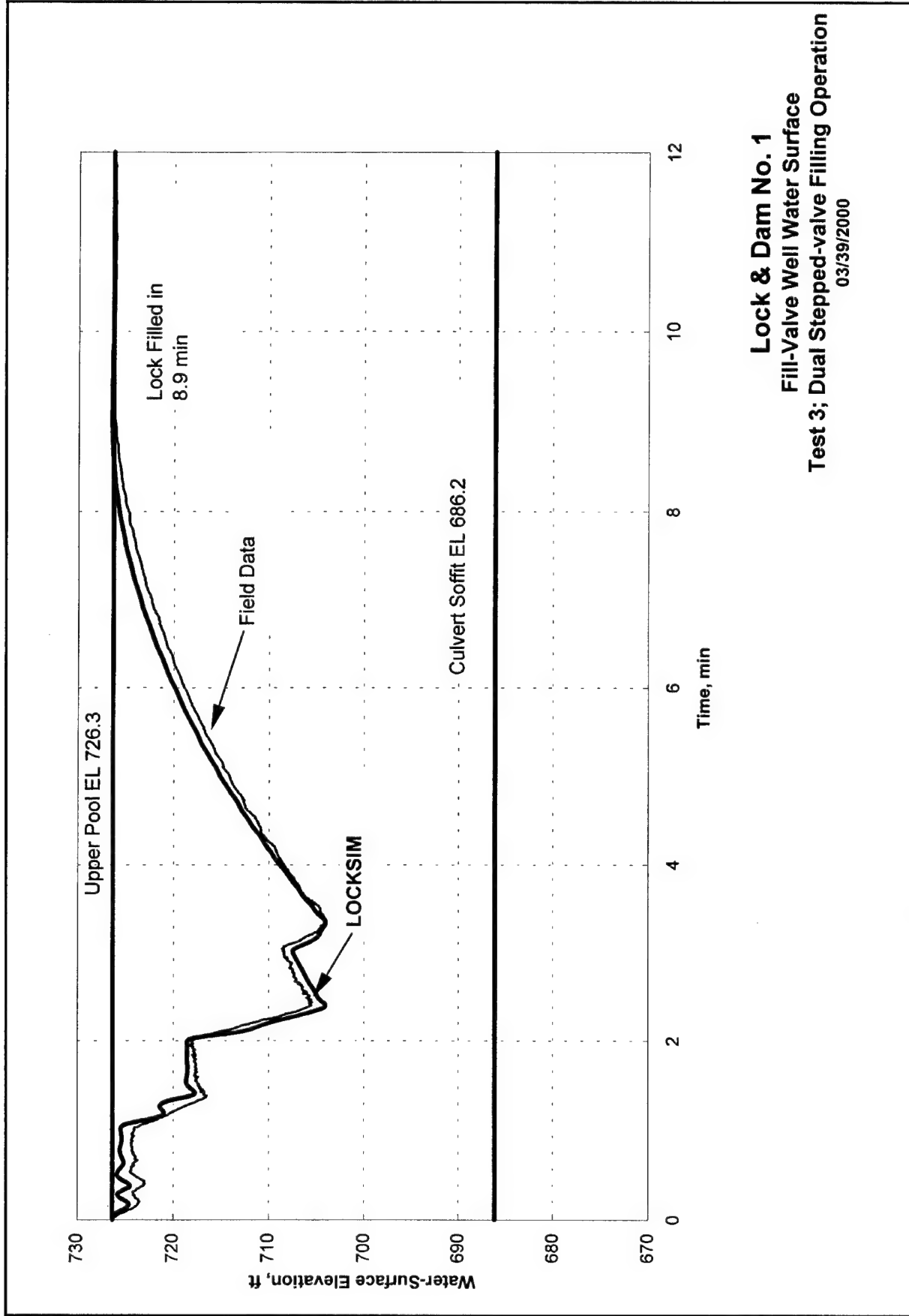
Figure 36. Water surface in fill-valve well, Test 3 – dual stepped-valve filling operation, upper pool el 726.3, lower pool el 689.2
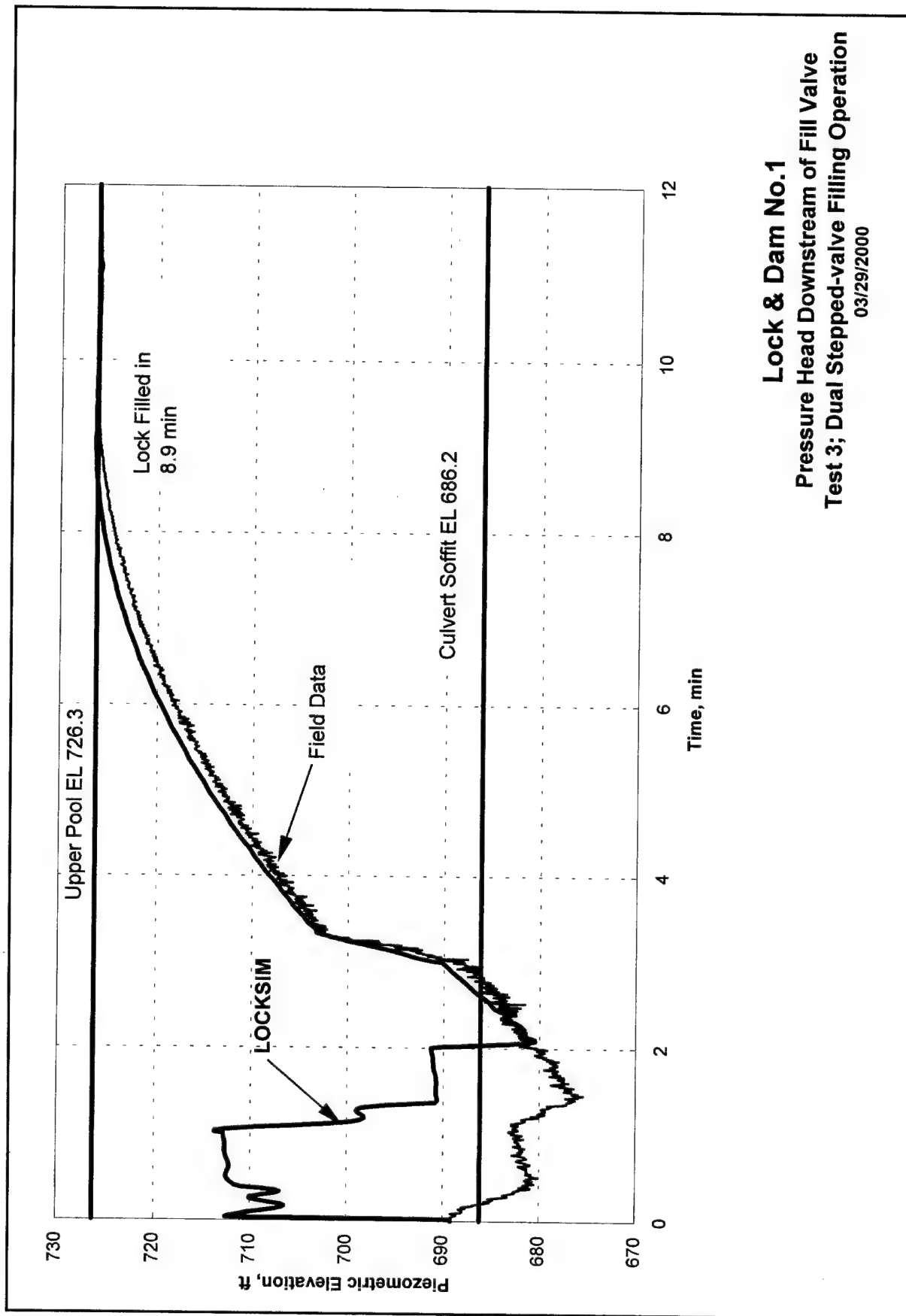
Figure 37. Pressure head downstream of fill valve, Test 3 – dual stepped-valve filling operation, upper pool el 726.3, lower pool el 689.2

Lock & Dam No. 1
Test 12; Lock Empty Operation
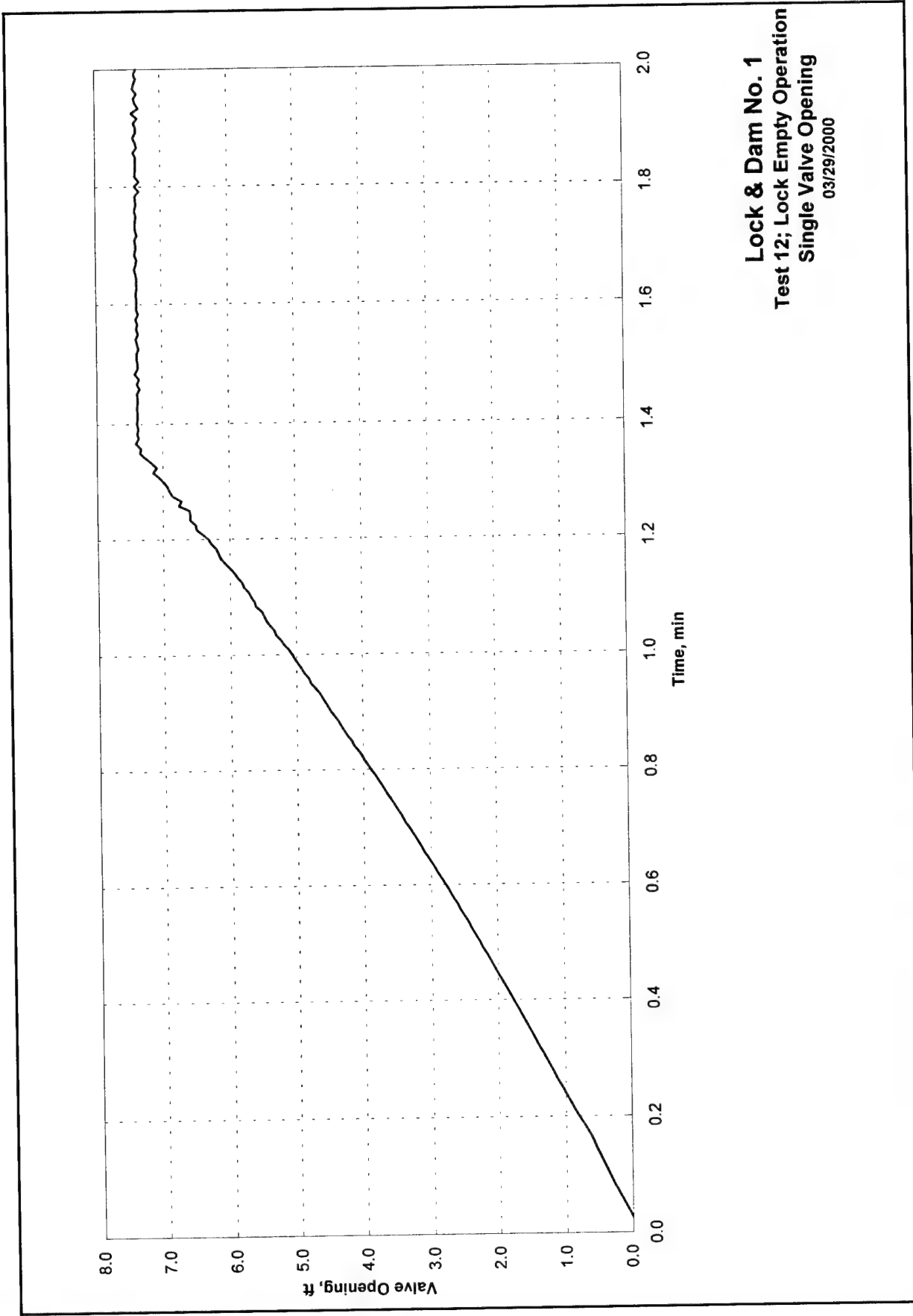**Single Valve Opening**
03/29/2000

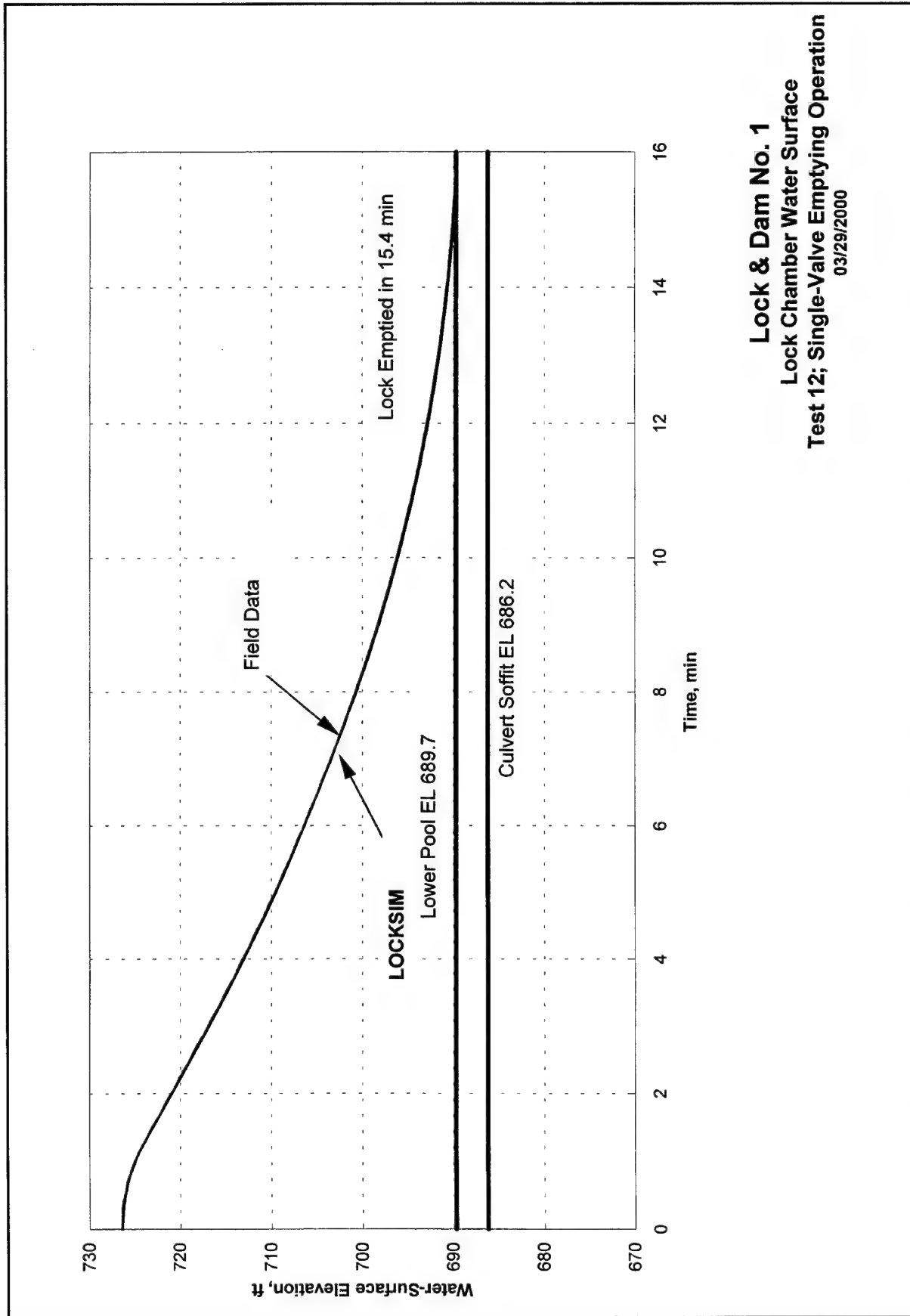Figure 38. Test 12 valve opening schedule, single-valve emptying operation

Figure 39. Lock chamber water surface, Test 12 – single-valve emptying operation, upper pool el 726.4, lower pool el 689.7
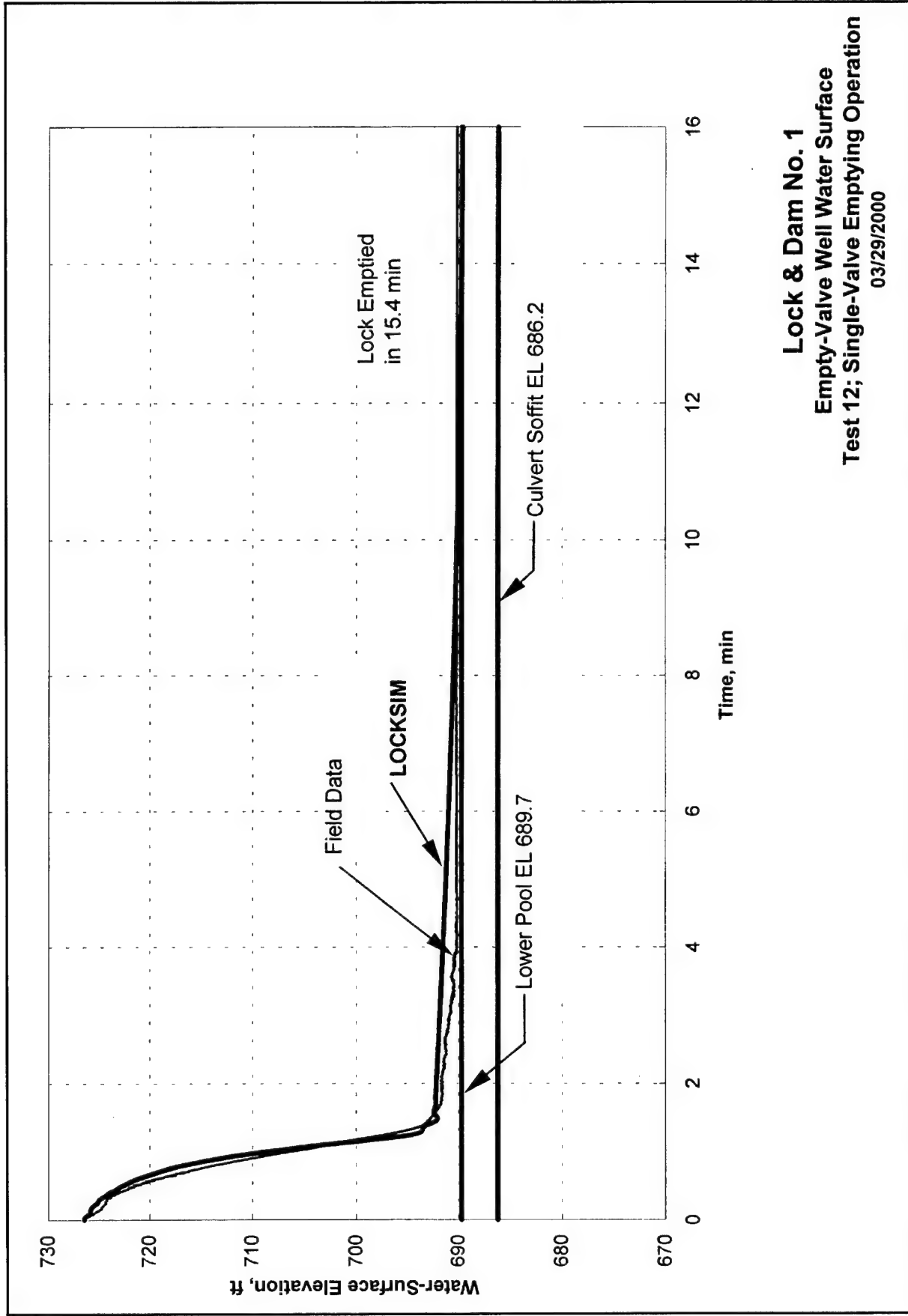
Figure 40. Water surface in empty-valve well, Test 12 – single-valve emptying operation, upper pool el 726.4, lower pool el 689.7
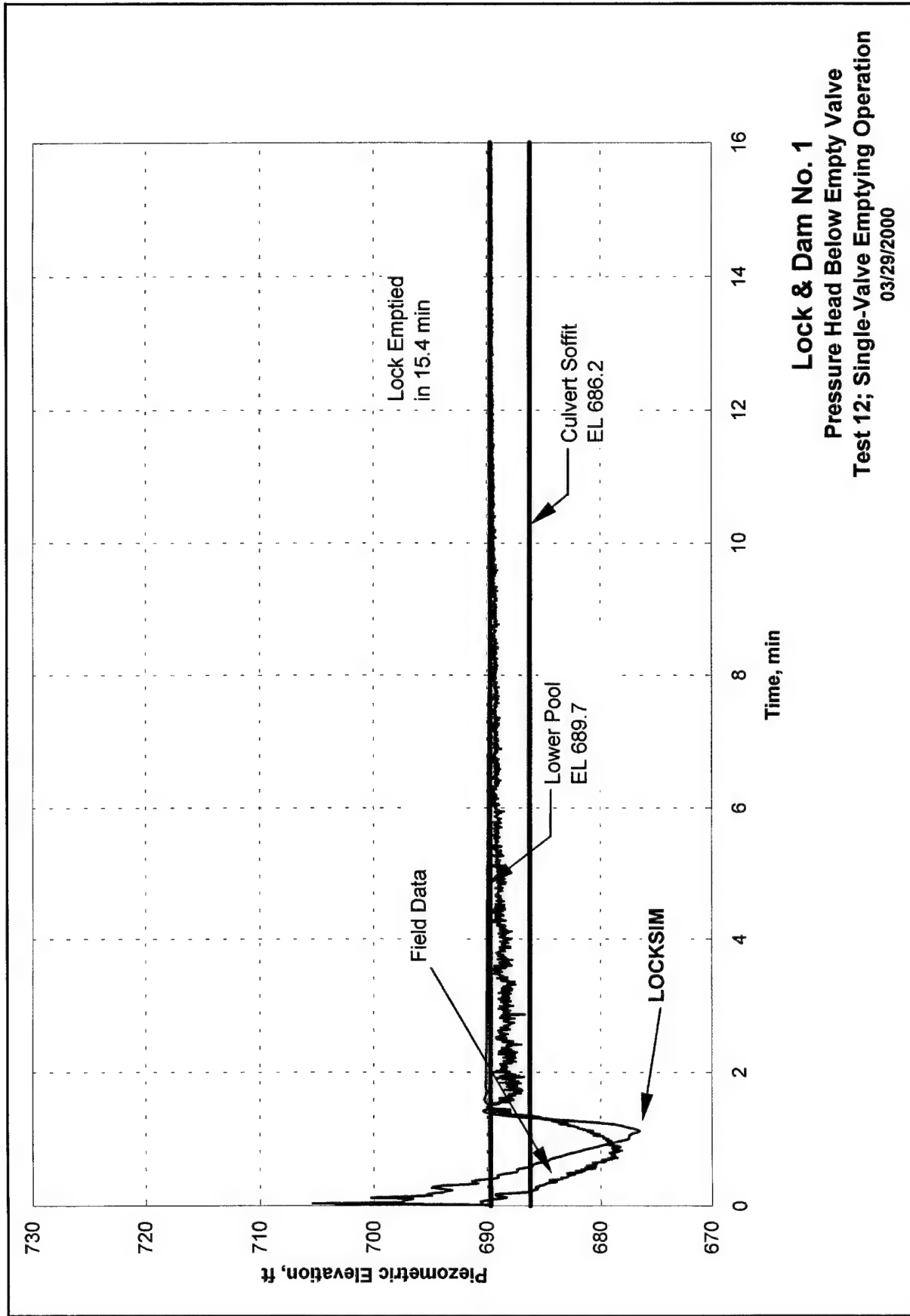
Figure 41. Pressure head downstream of empty valve, Test 12 – single-valve emptying operation, upper pool el 726.4, lower pool el 689.7
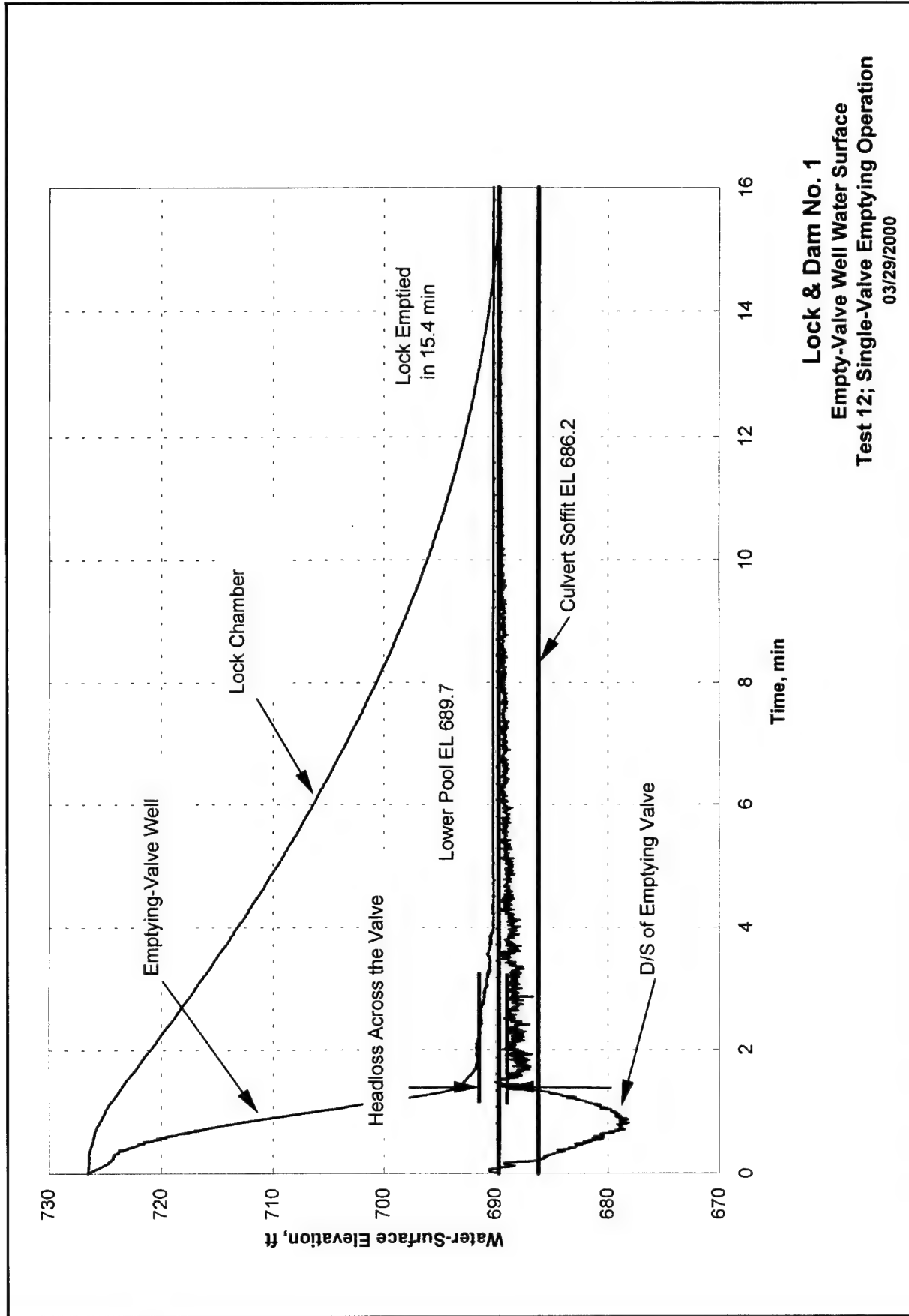
Figure 42. Headloss across the emptying valve, Test 12 – single-valve emptying operation, upper pool el 726.4, lower pool el 689.7
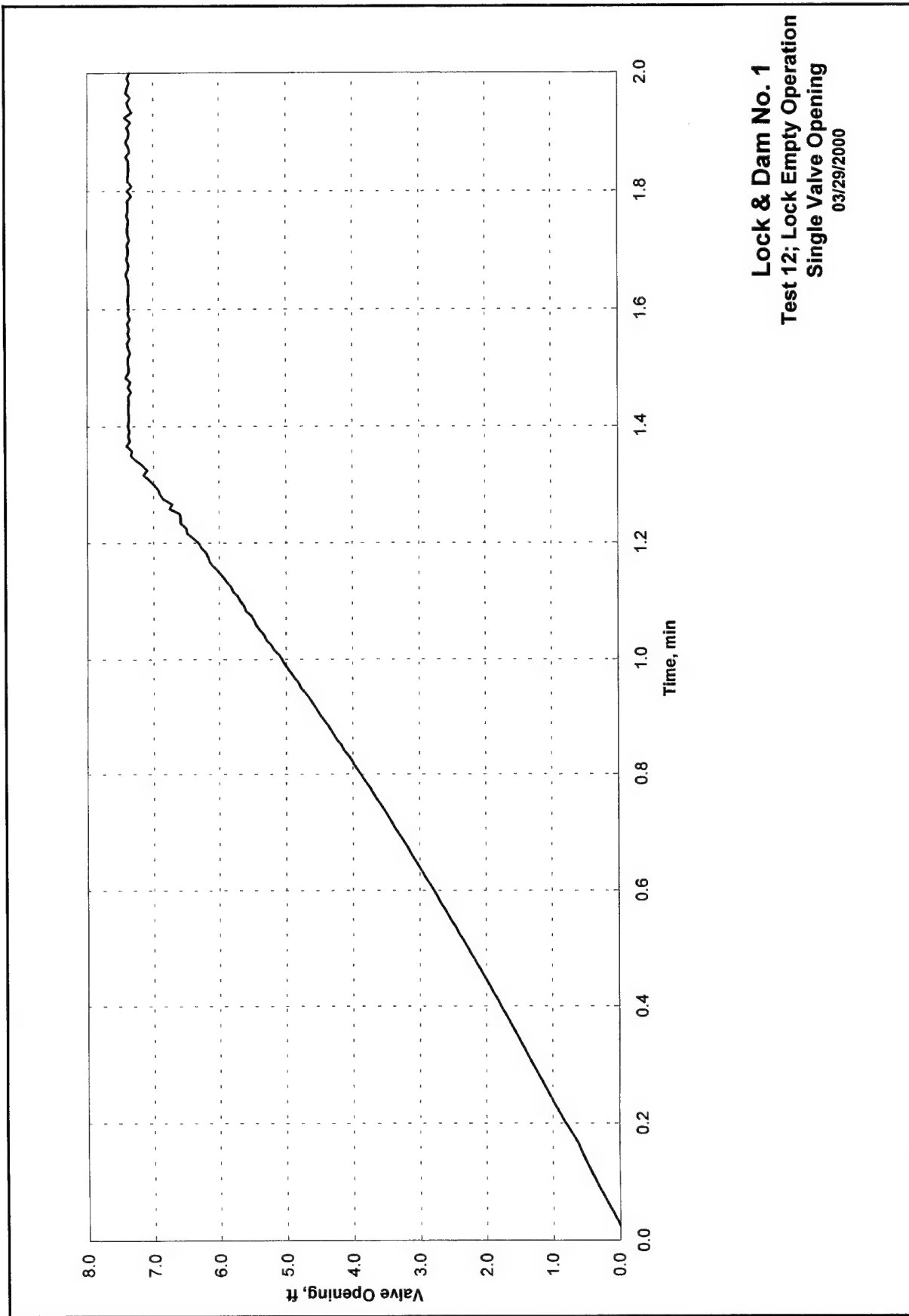
Figure 43. Test 12 – valve opening schedule, single-valve emptying operation
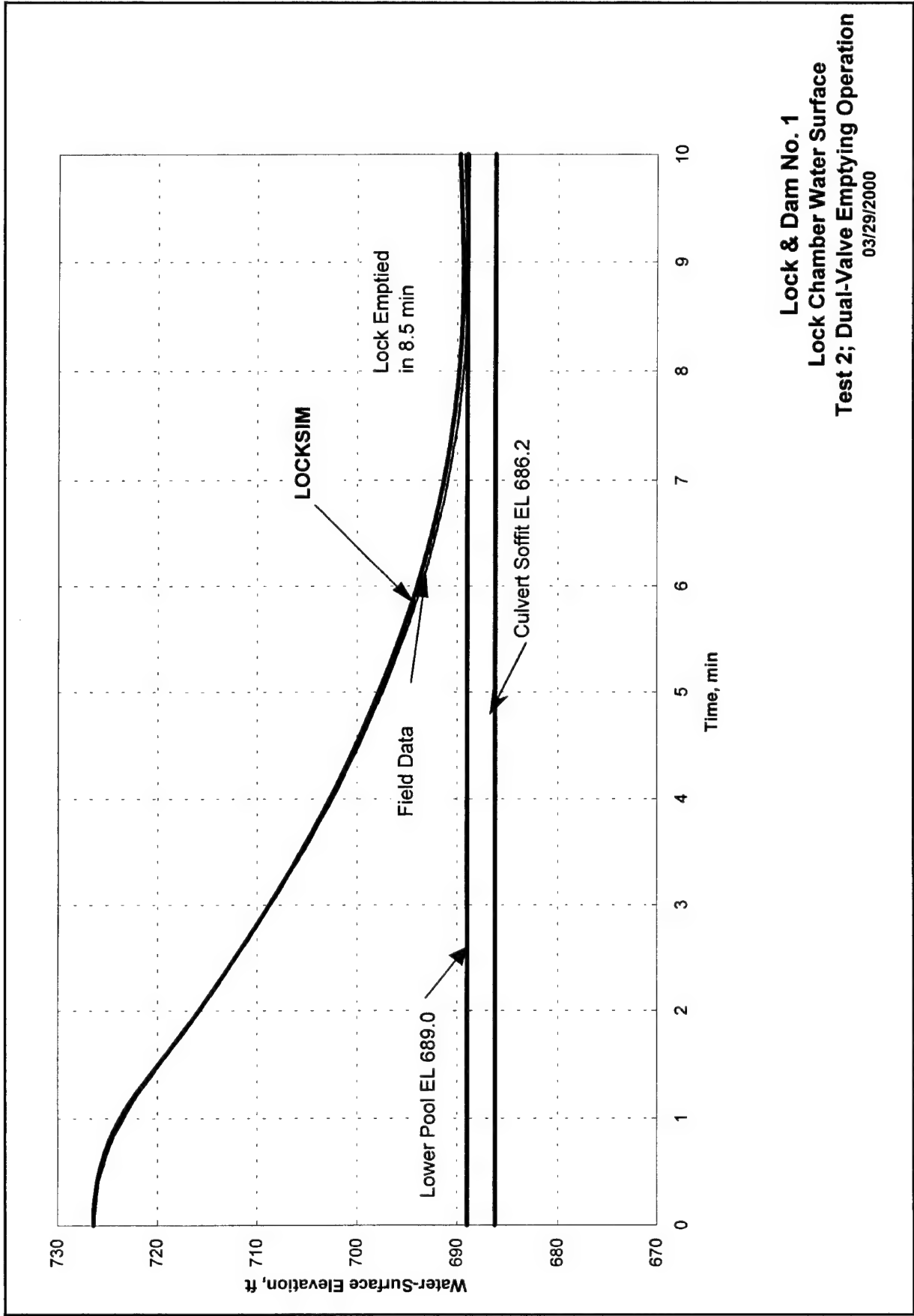
Figure 44. Lock chamber water surface, Test 2 – dual-valve emptying operation, upper pool el 726.3, lower pool el 689.0
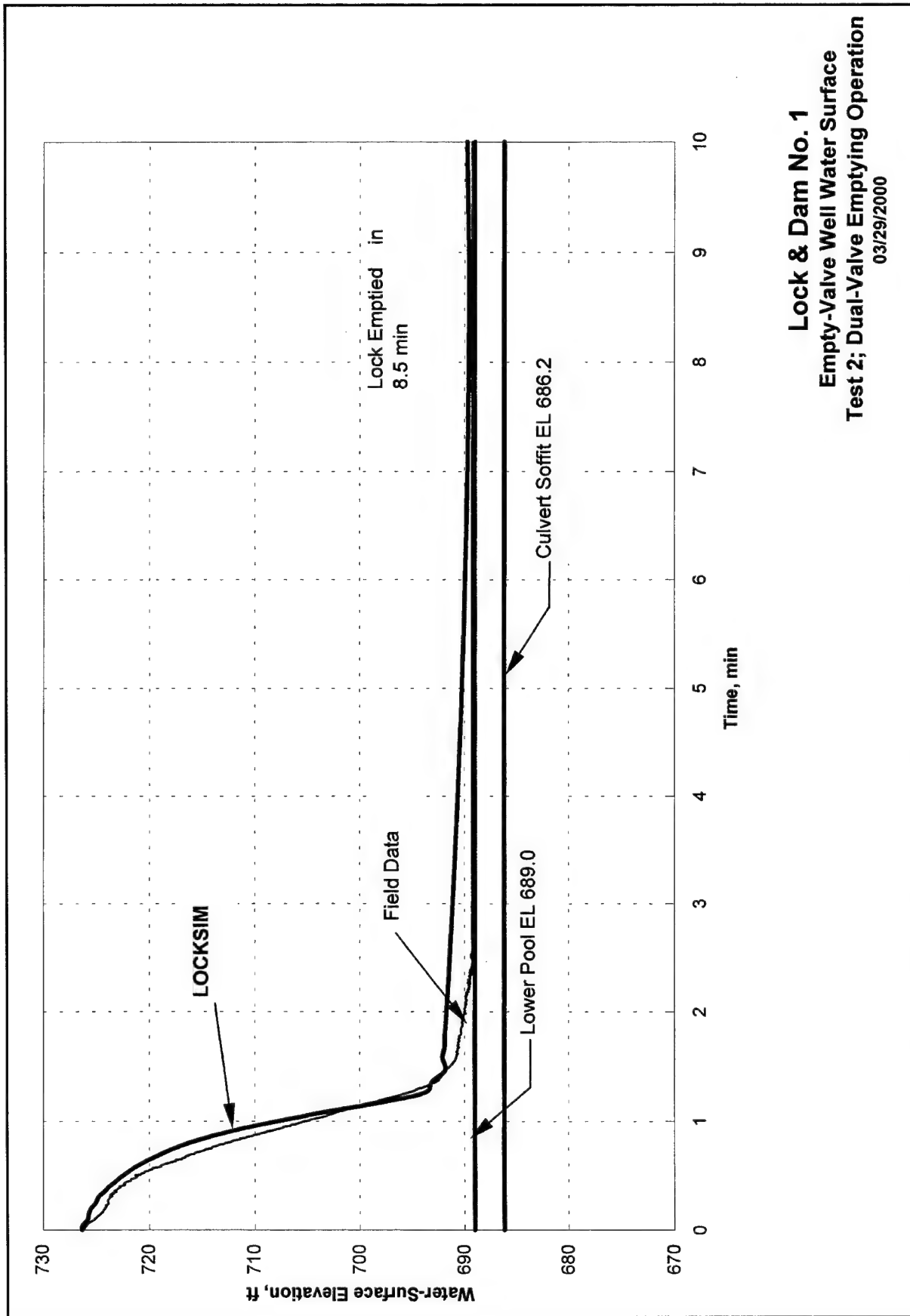
Figure 45. Water surface in empty-valve well, Test 2 – dual-valve emptying operation, upper pool el 726.3, lower pool el 689.0
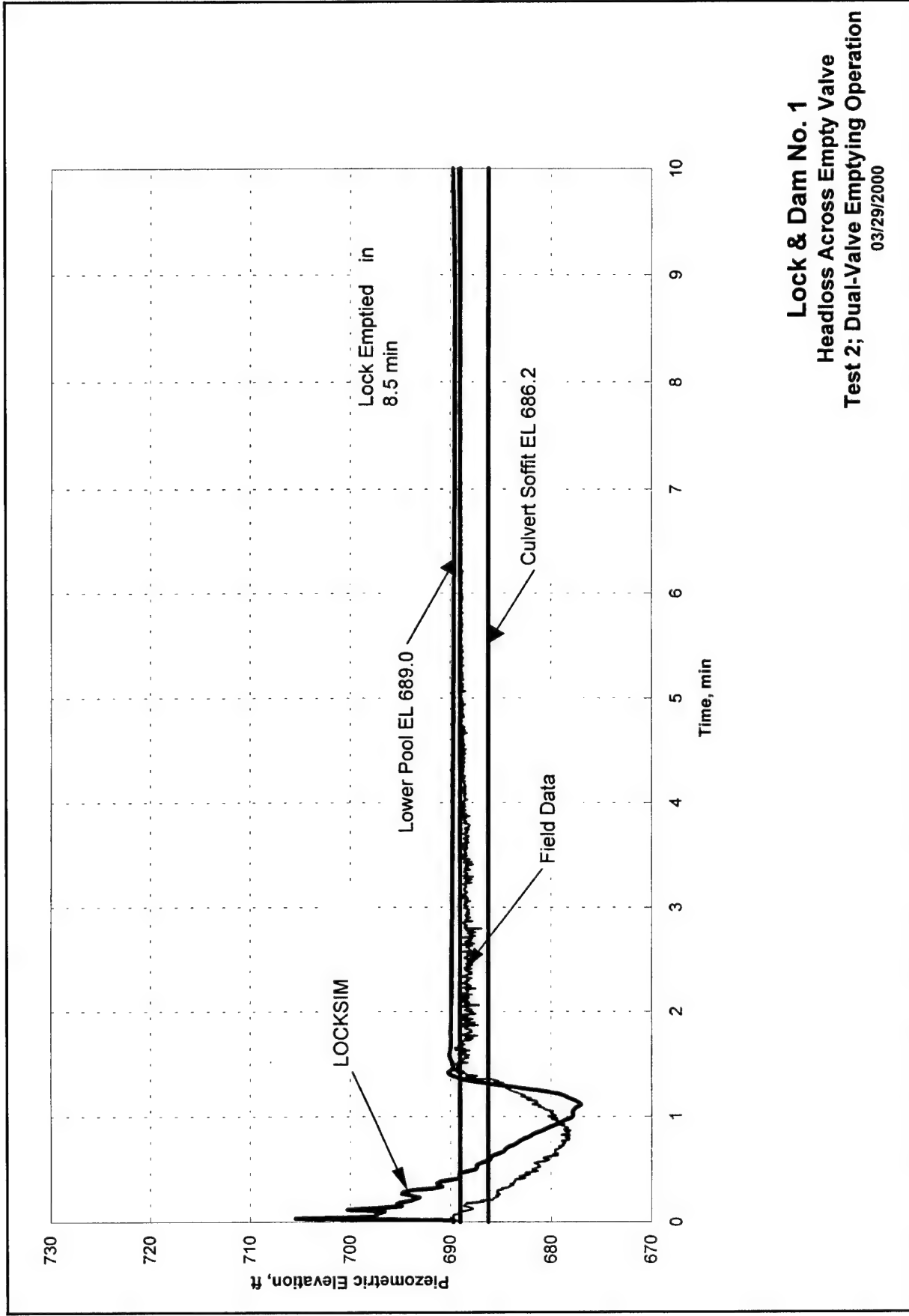
Figure 46. Pressure head downstream of empty valve, Test 2 – dual-valve emptying operation, upper pool el 726.3, lower pool el 689.0
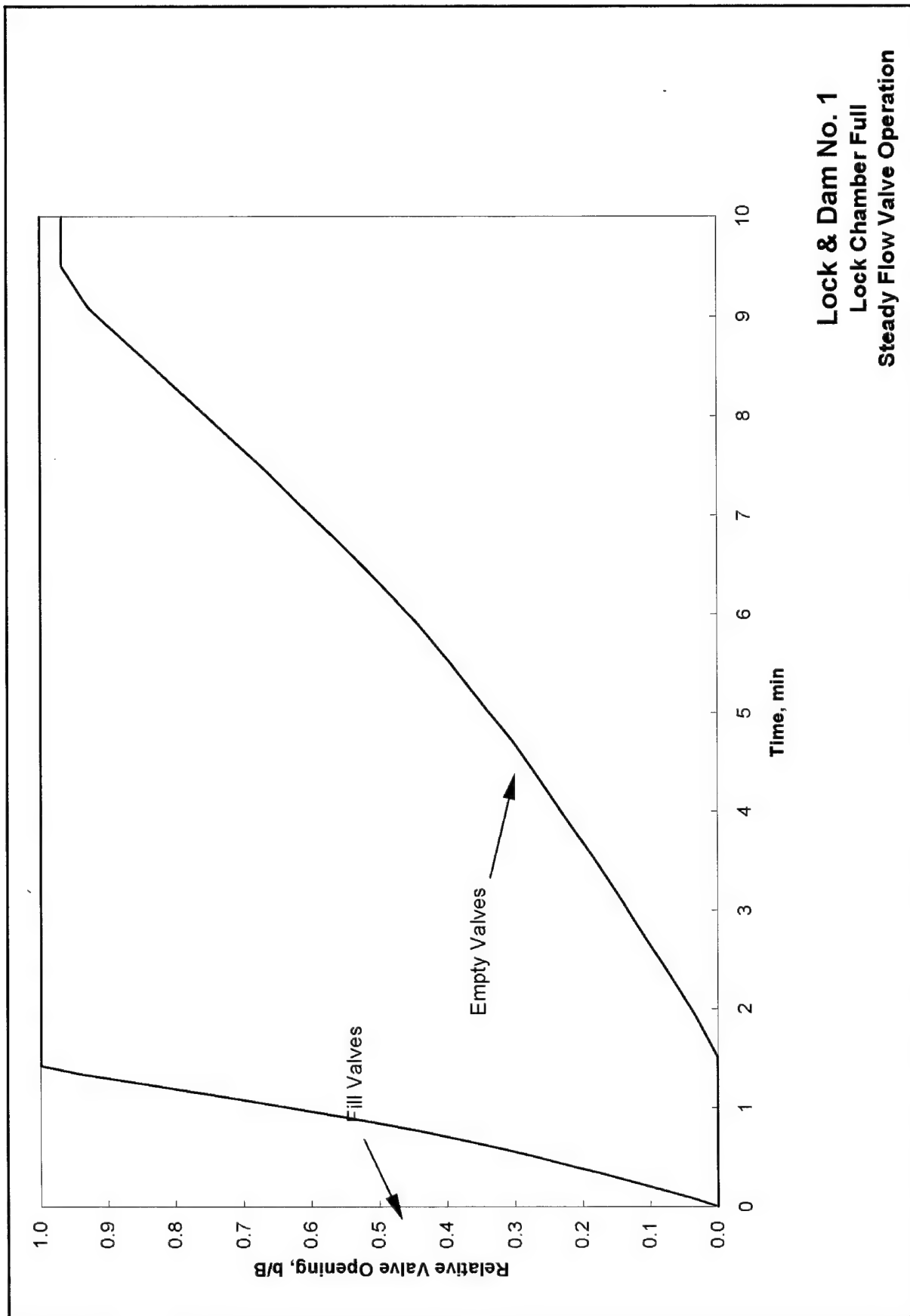
Figure 47. Valve schedule for establishment of steady flow, lock chamber initially full
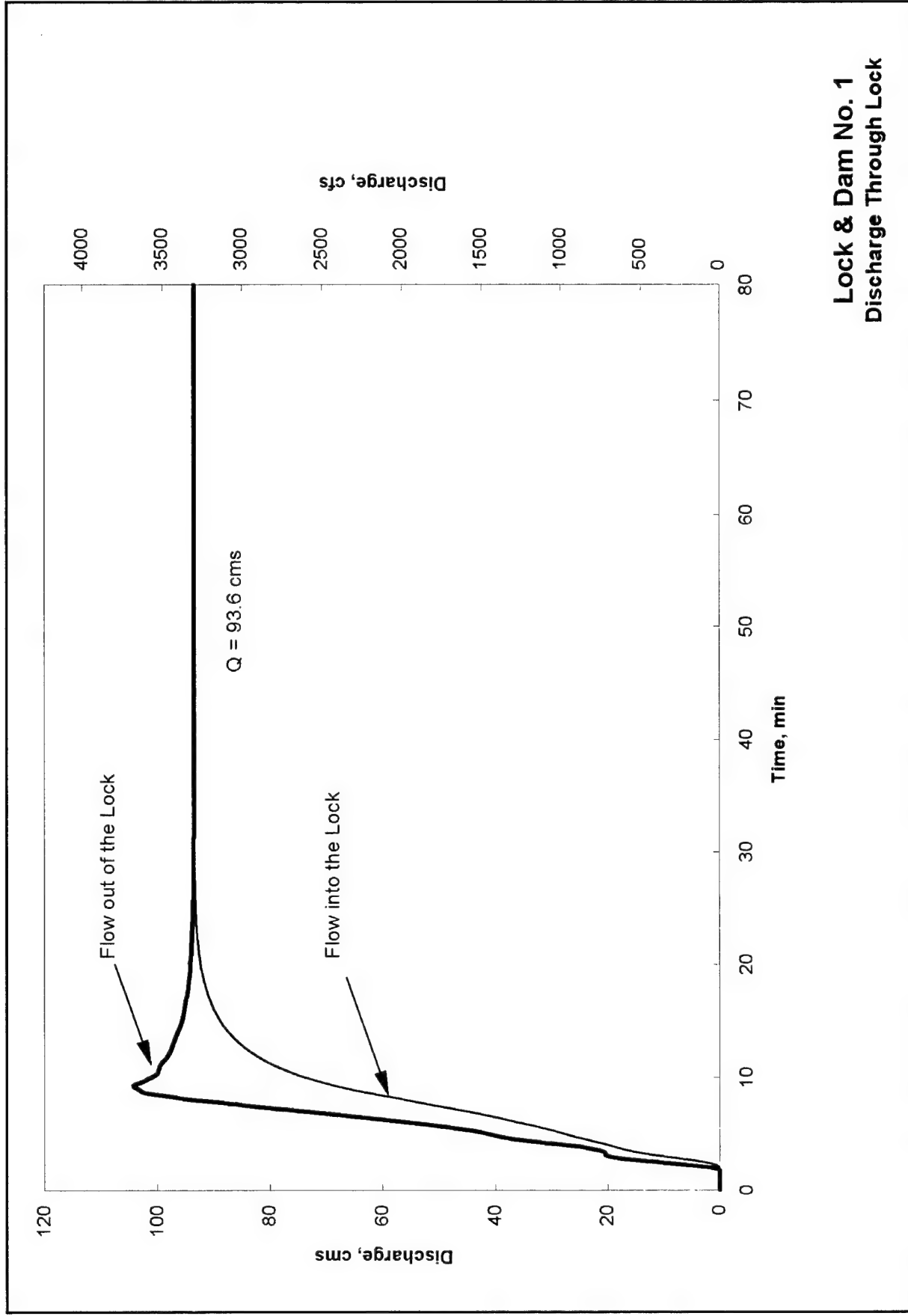
Figure 48. Time-history of discharge through lock, lock chamber initially full, tainter valves initially closed, upper pool el 726.3, lower pool el 689.2
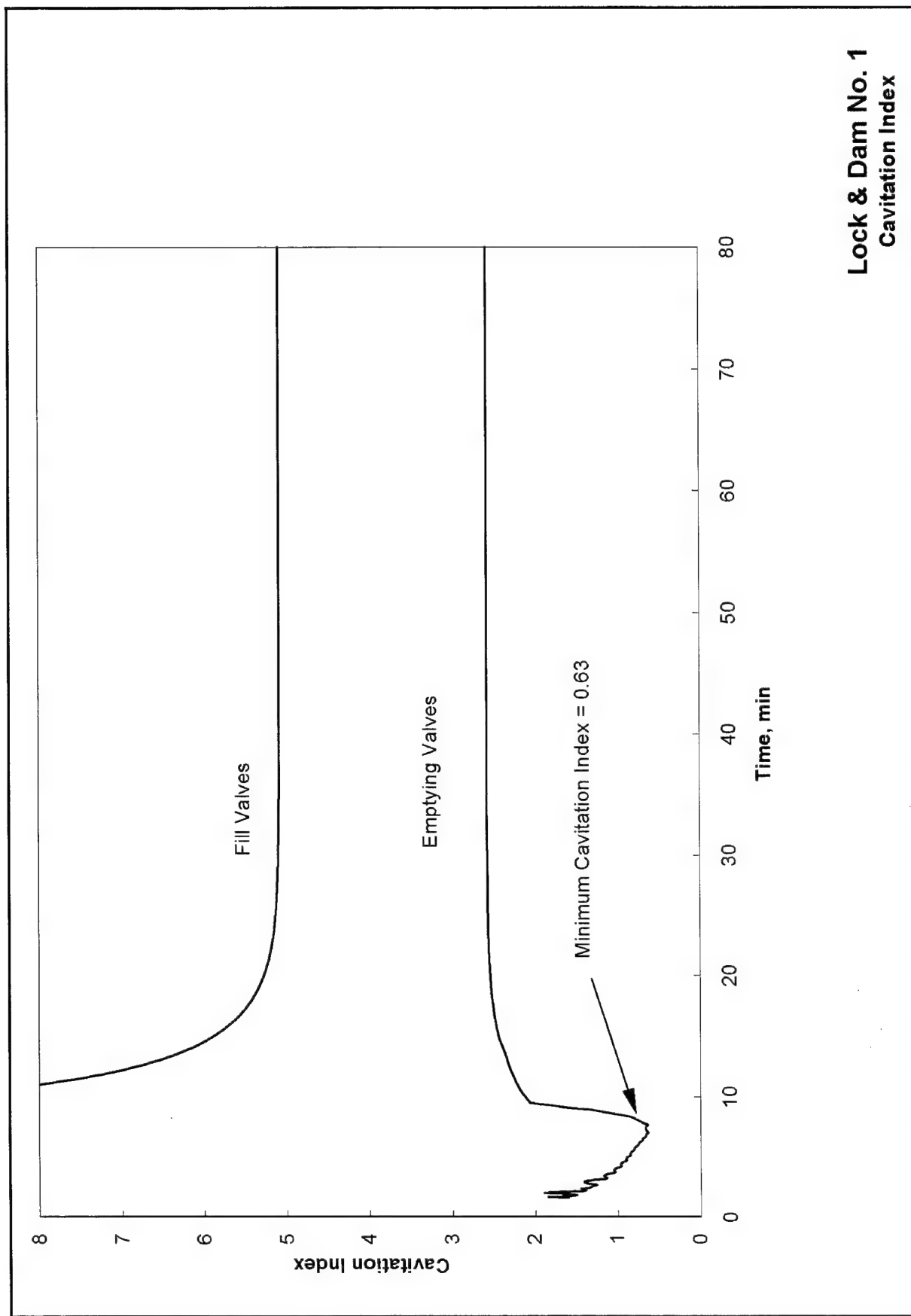
Figure 49. Time-history of cavitation index, lock chamber initially full, tainter valves initially closed, upper pool el 726.3, lower pool el 689.2
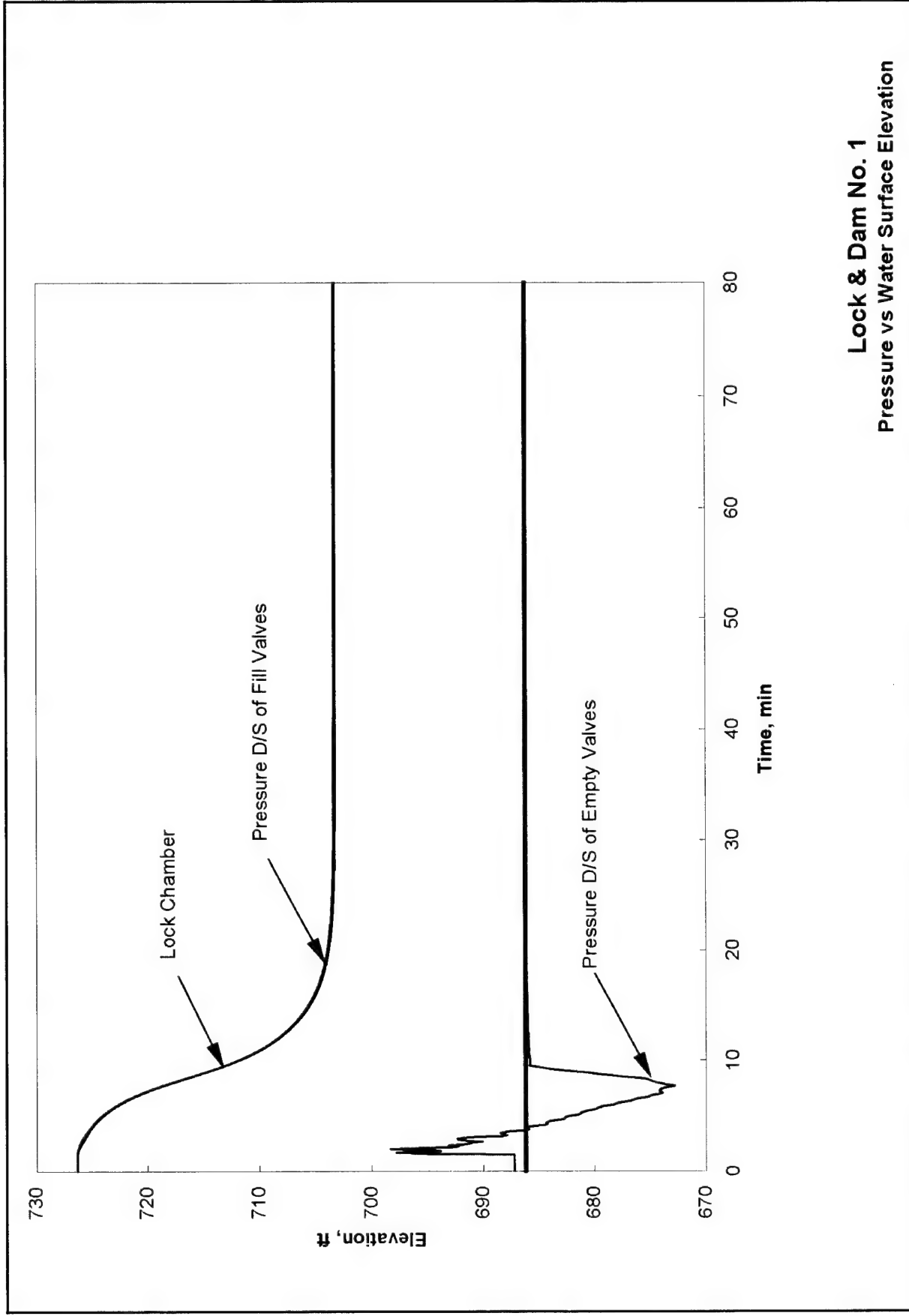
Figure 50. Time-history of pressure and water surface elevation, lock chamber initially full, tainter valves initially closed, upper pool el 726.3, lower pool el 689.2

Difference Between Upper and Lower Pools, H, ft

Discharge Through the Lock, Q, cfs

$$Q = C_d \, A_v \, (2gH)^{0.5}$$
where: $C_d = 0.55$

LP = 687.2
LP = 690.0
LP = 687.2
LP = 687.2
LP = 689.0
LP = 690.0
LP = 690.0
LP = 693.0

Discharge Through the Lock, Q, cms

Difference Between Upper and Lower Pools, H, m

Lock & Dam No. 1
Lock Discharge Rating Curve
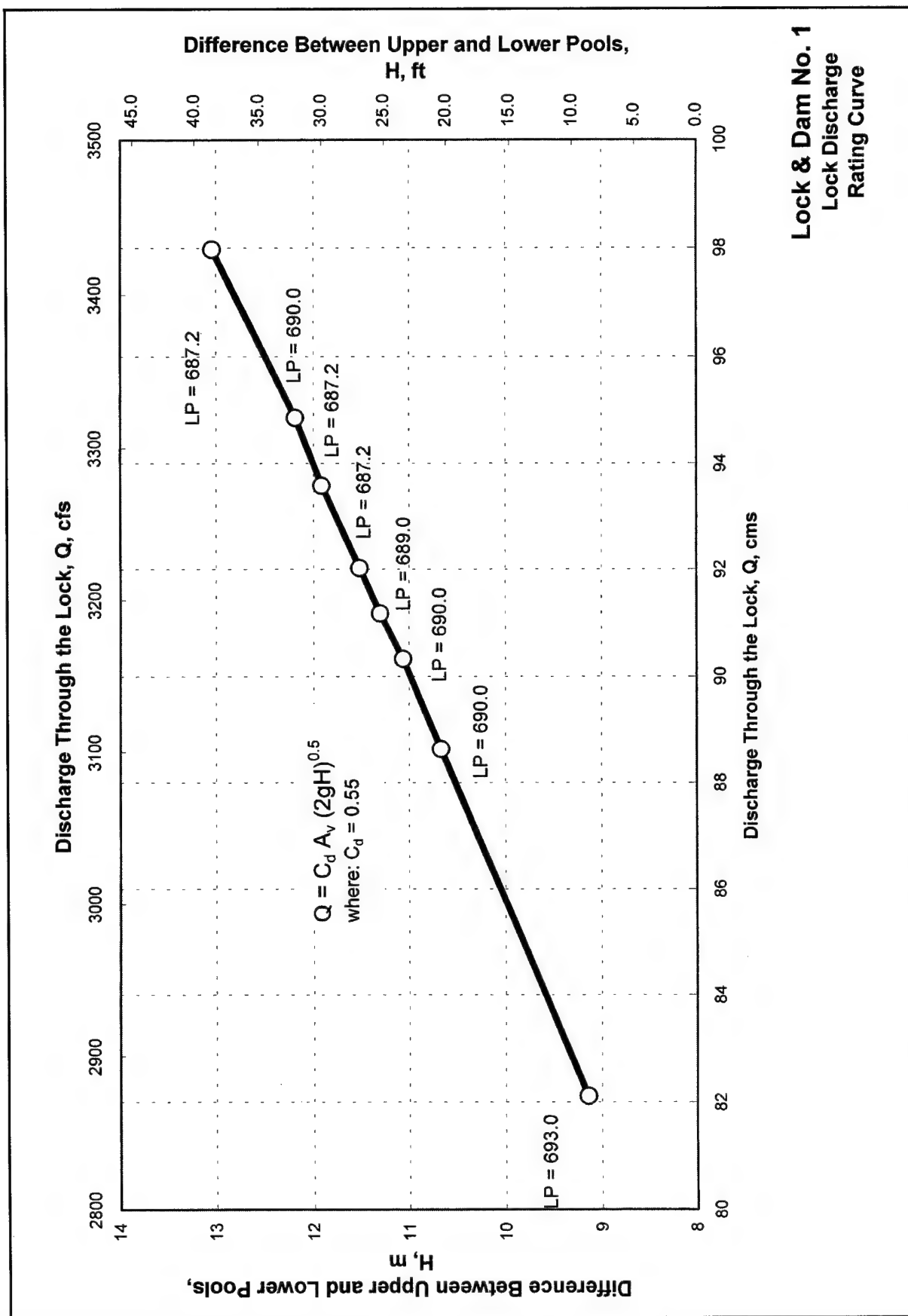
Figure 51. Lock discharge-rating curve, all tainter valves fully opened, and miter gates closed

Figure 52. Valve schedules for 60% empty-valve opening

Figure 53. Time-history of discharge through lock, 60% empty-valve opening, upper pool el 726.3, lower pool el 687.2
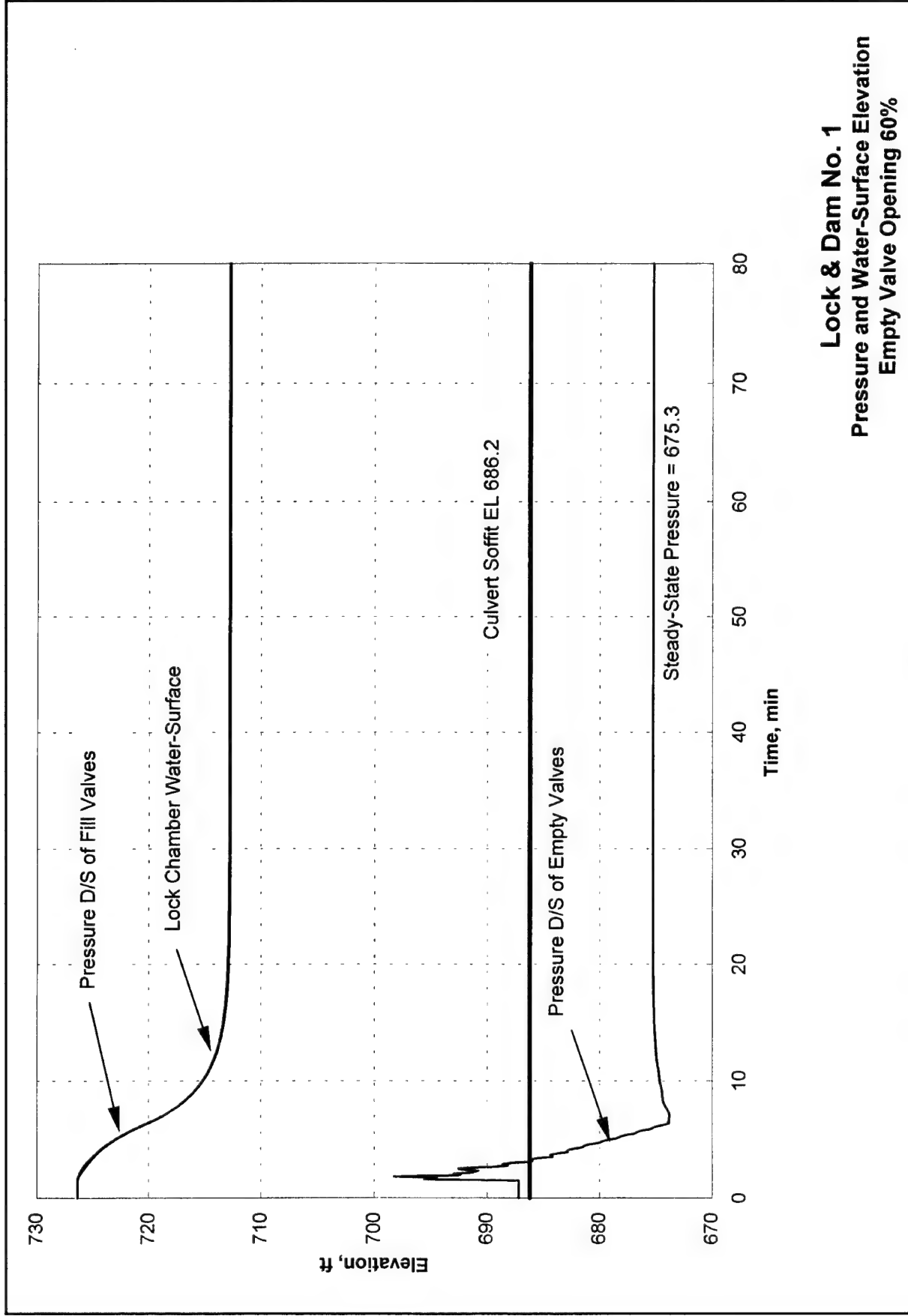
Figure 54. Time-history of pressures and water-surface elevation, 60% empty-valve opening, upper pool el 726.3, lower pool el 687.2
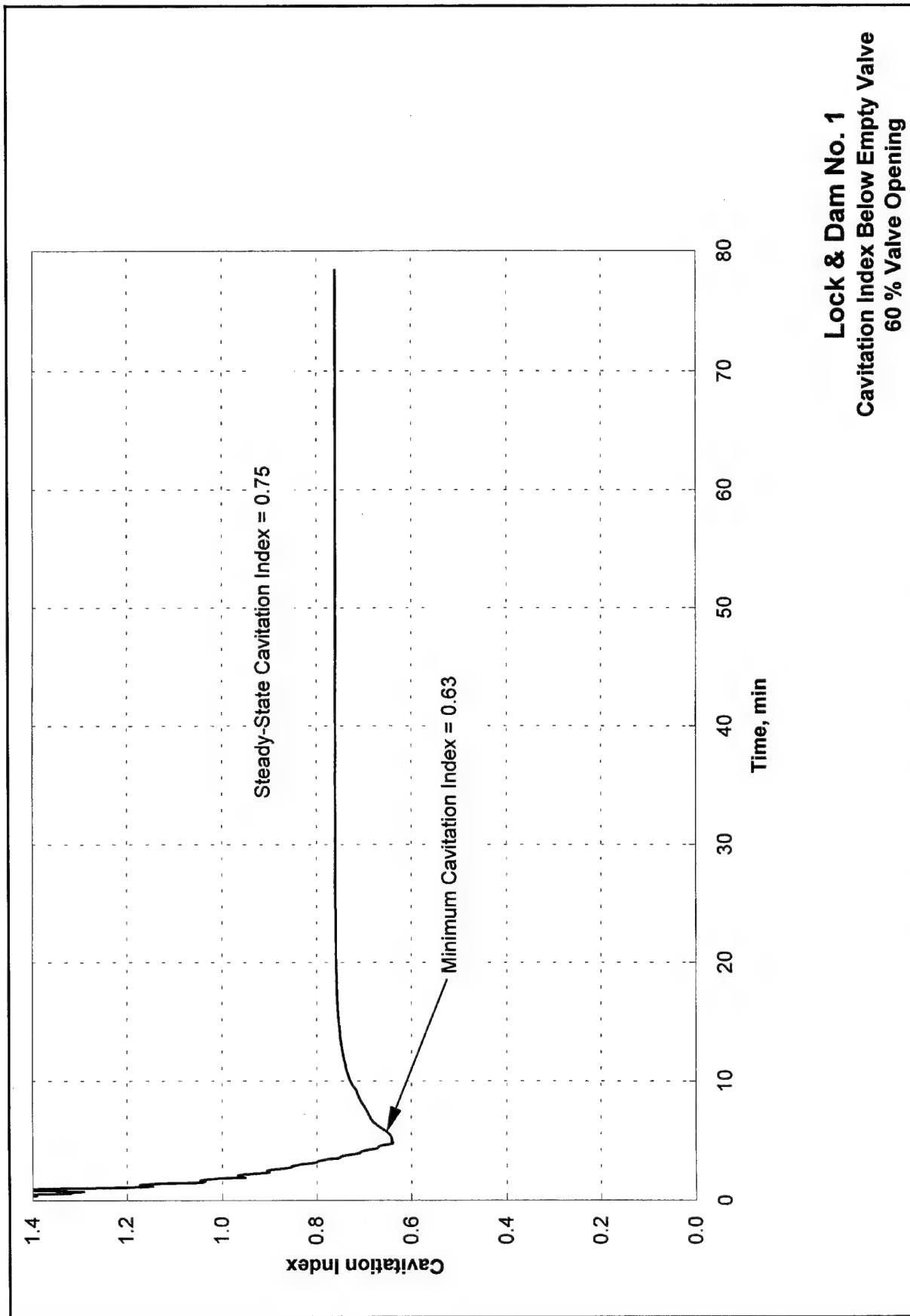
Figure 55. Time-history of cavitation index below emptying valve, 60% empty-valve opening, upper pool el 726.3, lower pool el 687.2

Lock & Dam No. 1
Valve Operation Schedule
Fill Valve 100%; Empty Valve 40%
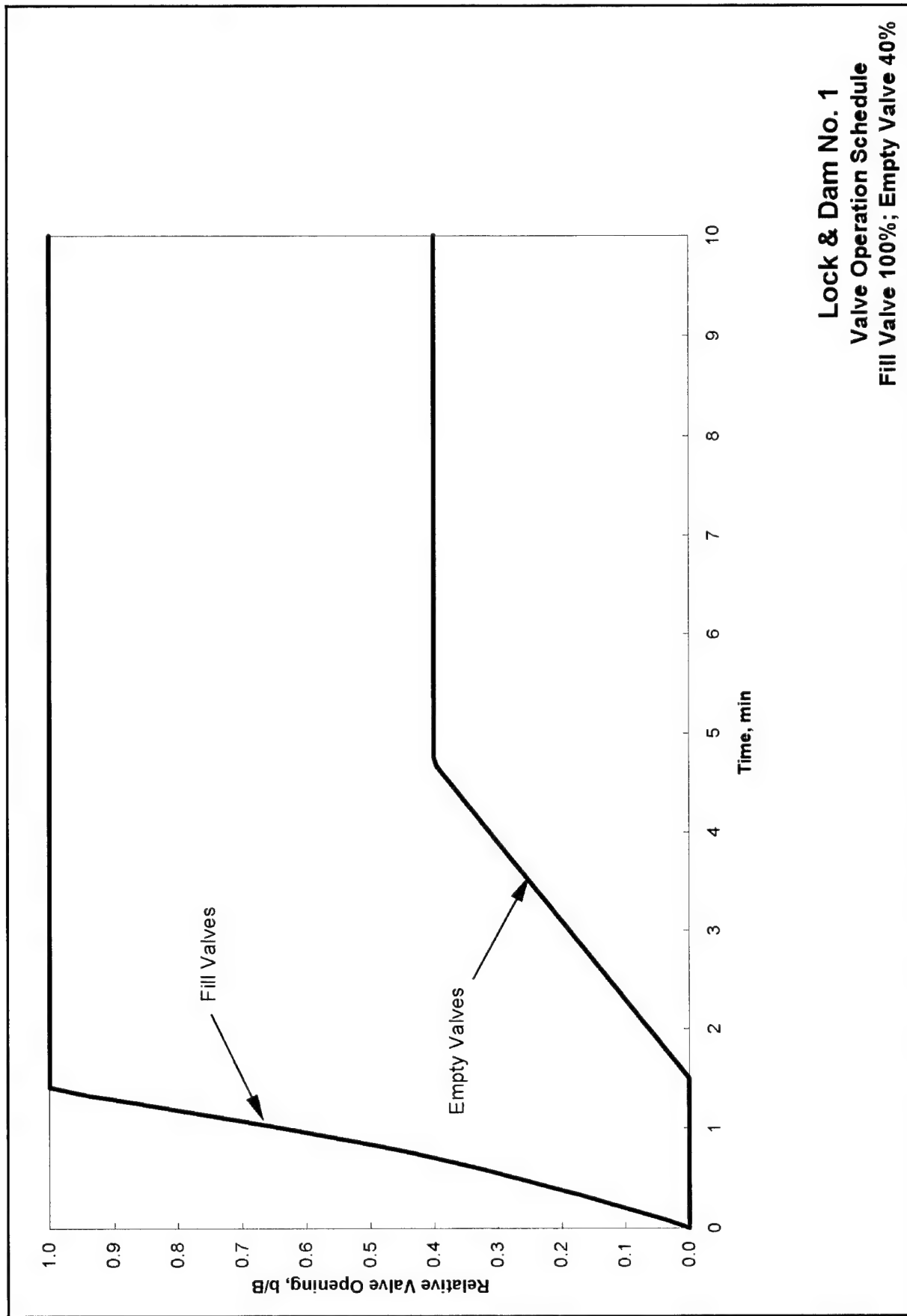
Figure 56. Valve schedules for 40% empty-valve opening
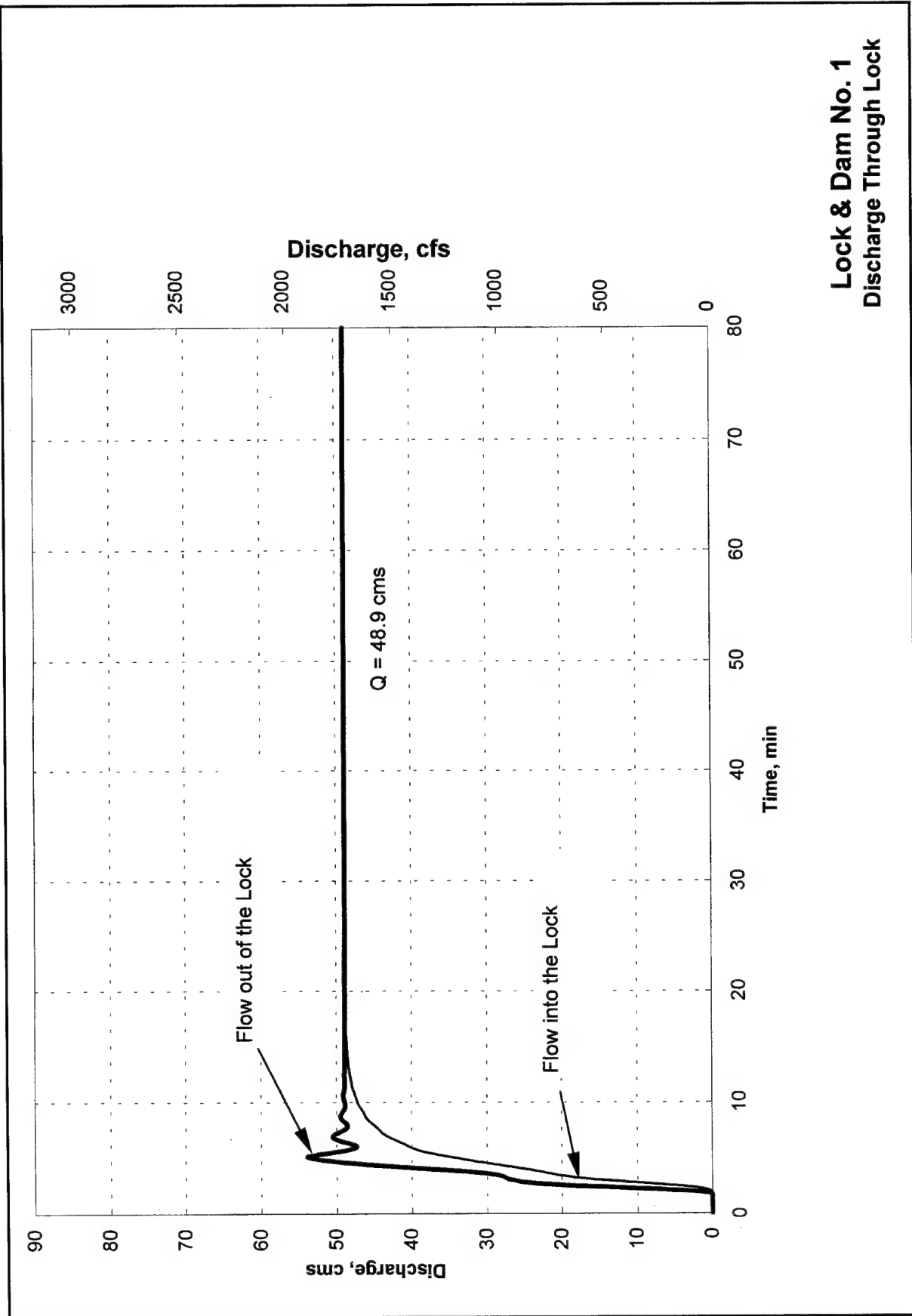
Figure 57. Time-history of discharge through lock, 40% empty-valve opening, upper pool el 726.3, lower pool el 687.2
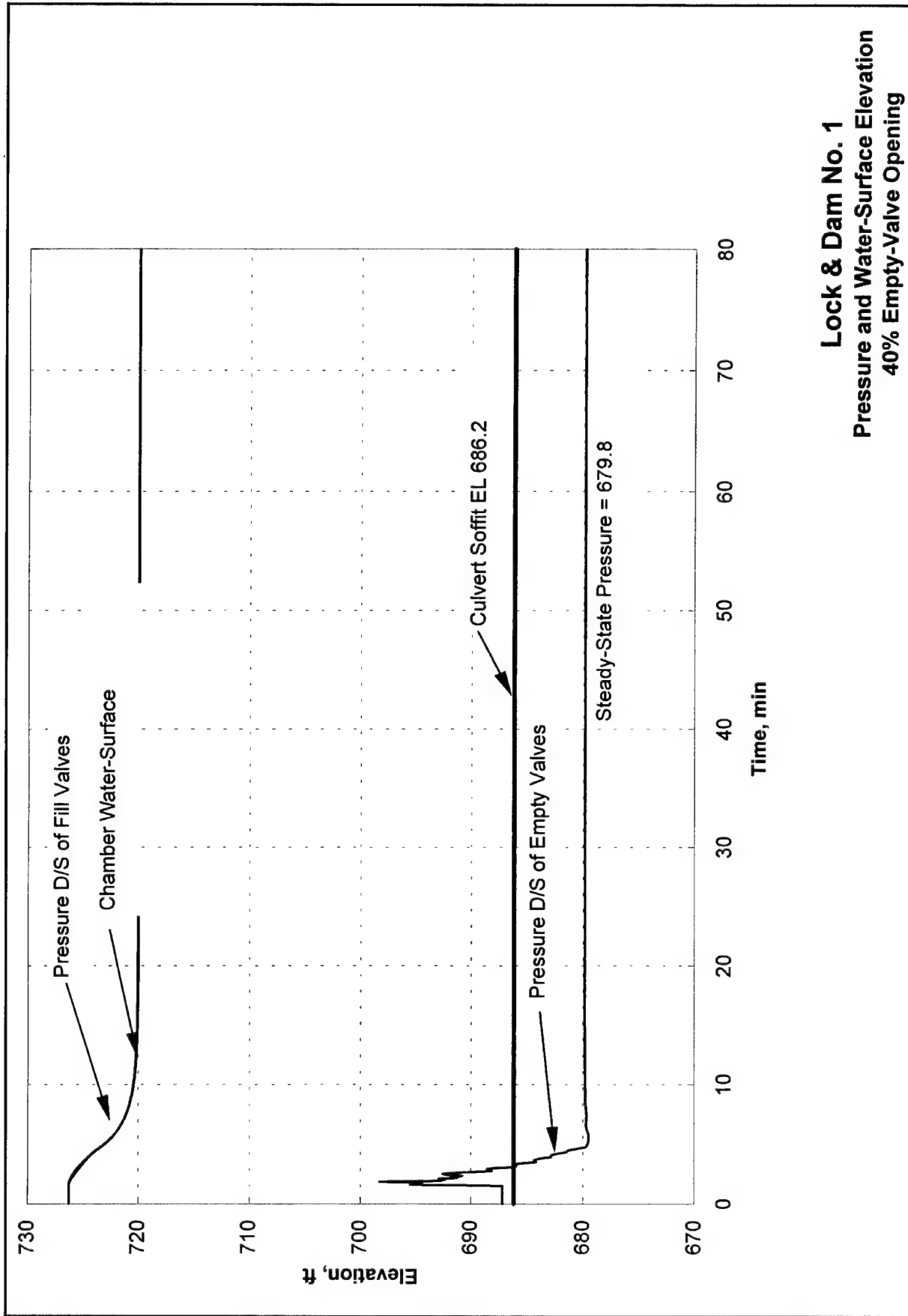
Figure 58. Time-history of pressure and water-surface elevation, 40% empty-valve opening, upper pool el 726.3, lower pool el 687.2
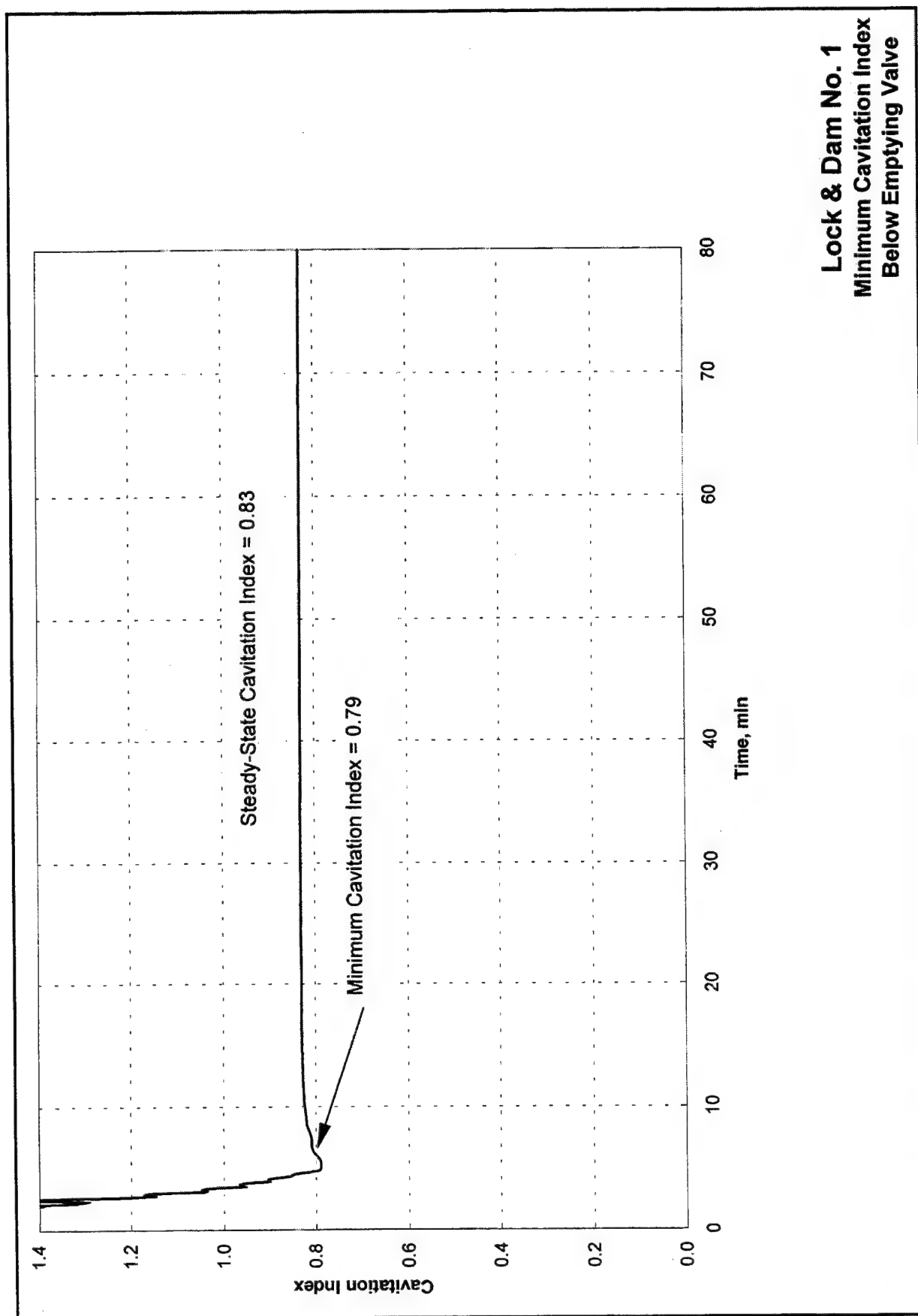
Figure 59. Time-history of cavitation index below emptying valves, 40% empty-valve opening, upper pool el 726.3, lower pool el 687.2

Lock & Dam No. 1
Valve Operation Schedules
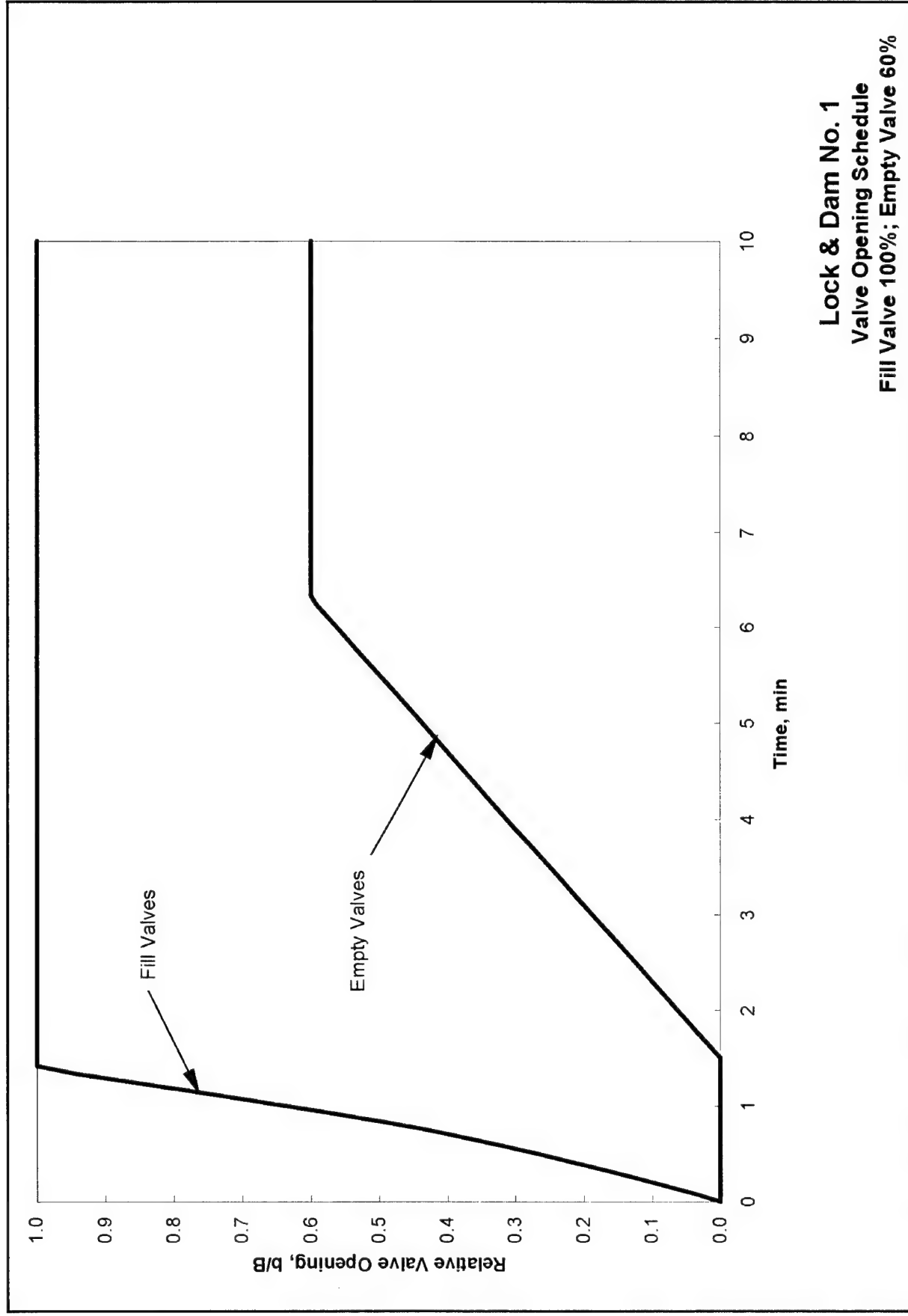**Fill-Valve 100%; Empty-Valve 20%**
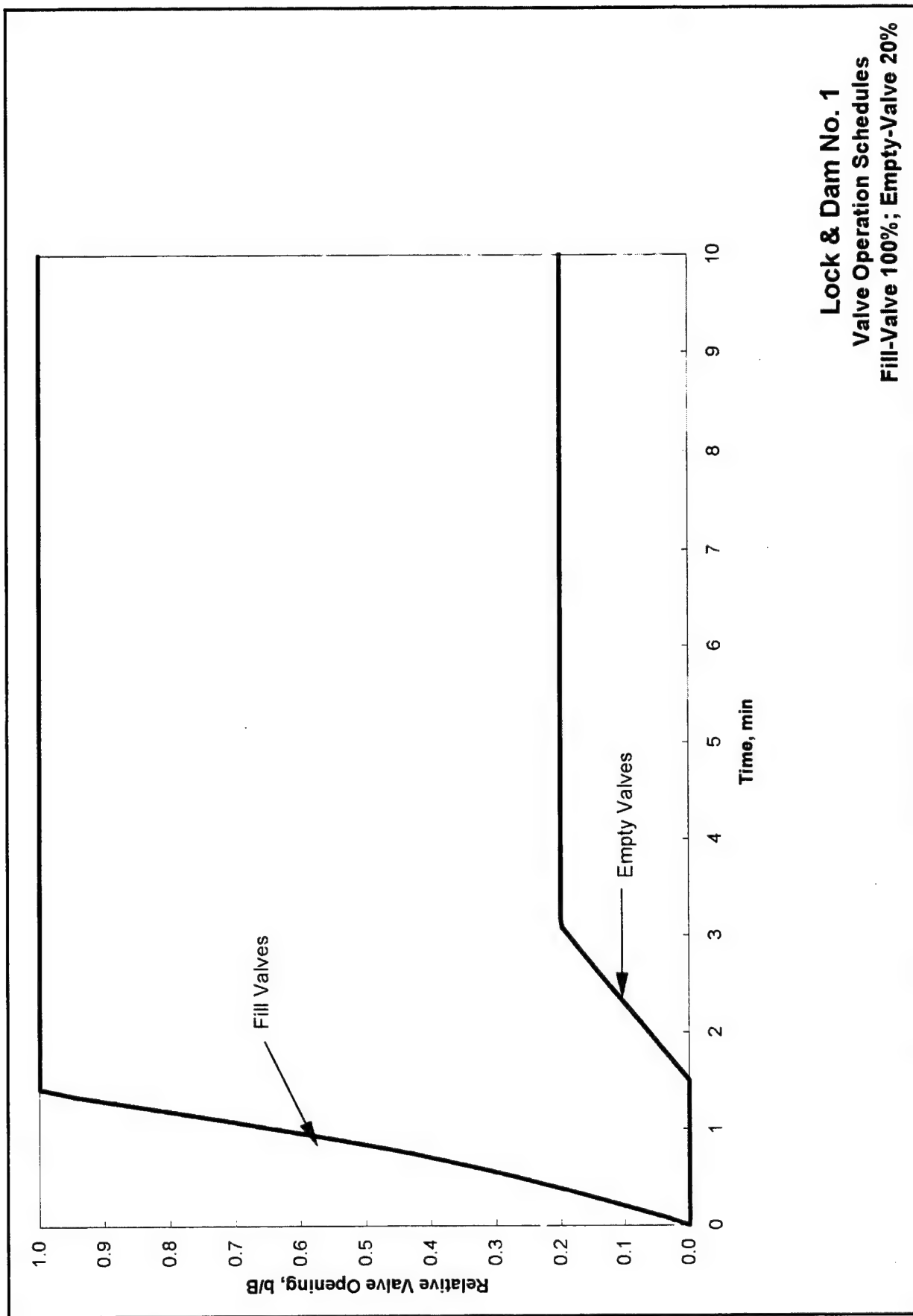
Figure 60. Valve schedules for 20% empty-valve opening
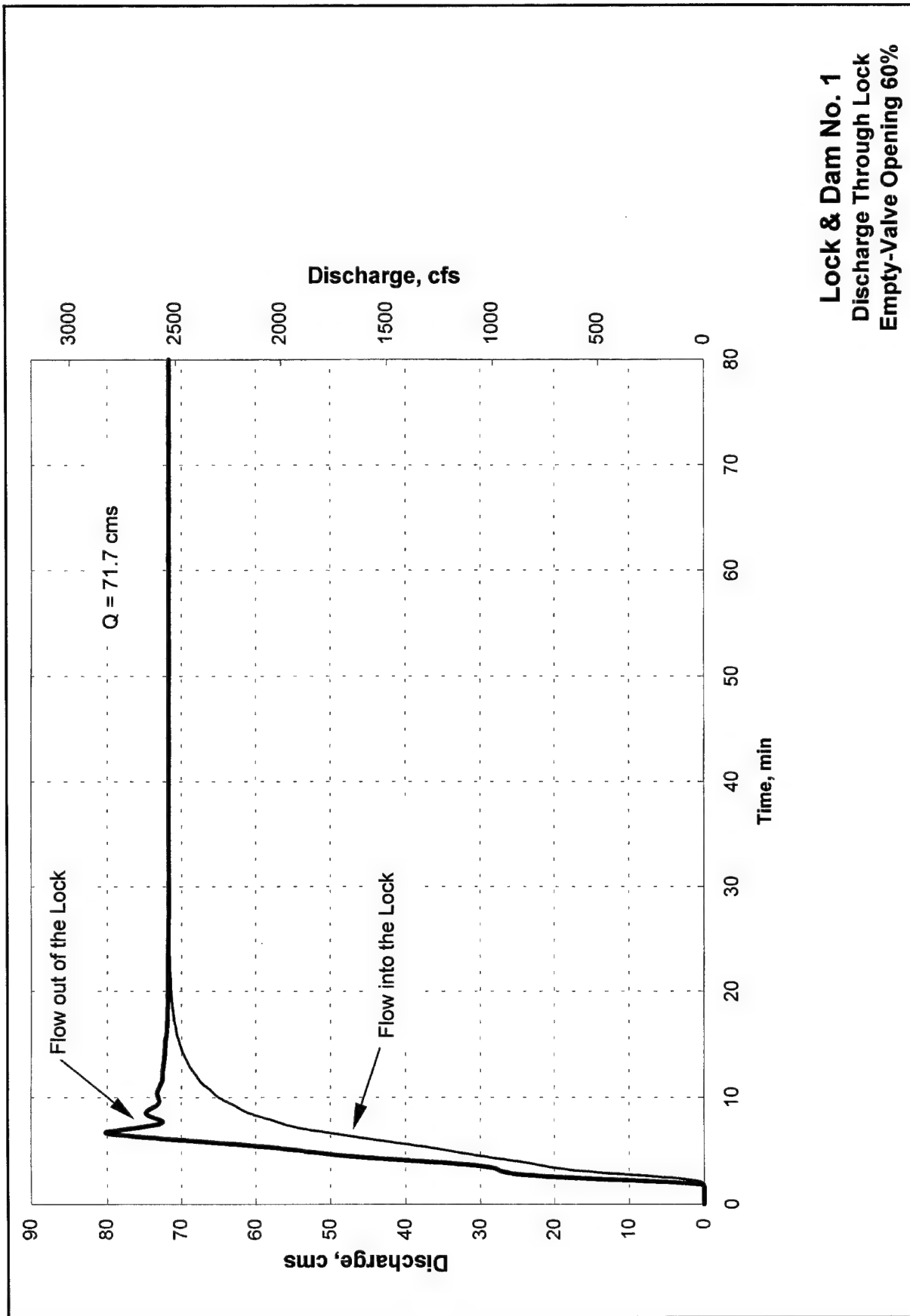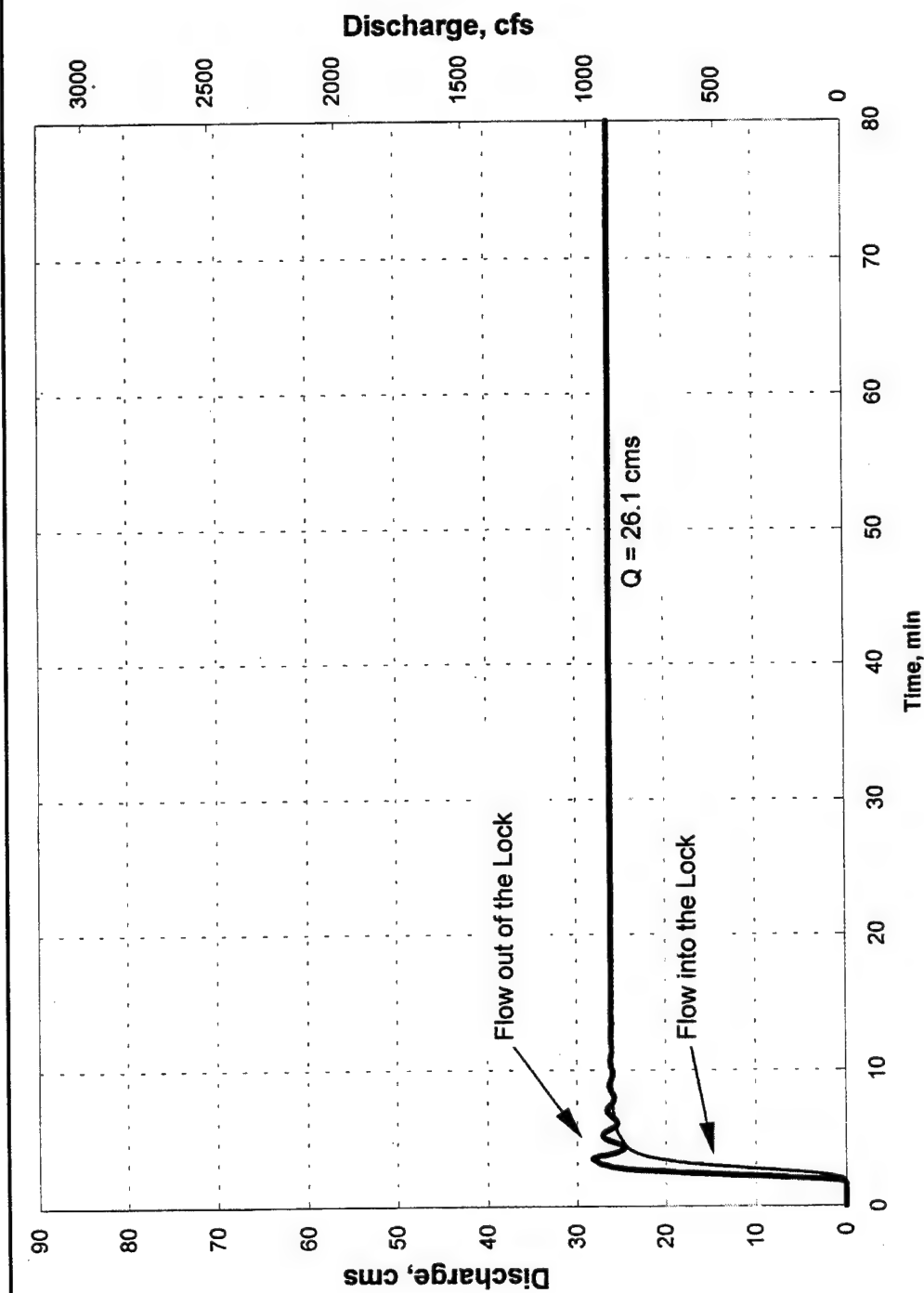
Figure 61. Time-history of discharge through lock, 20% empty-valve opening, upper pool el 726.3, lower pool el 687.2
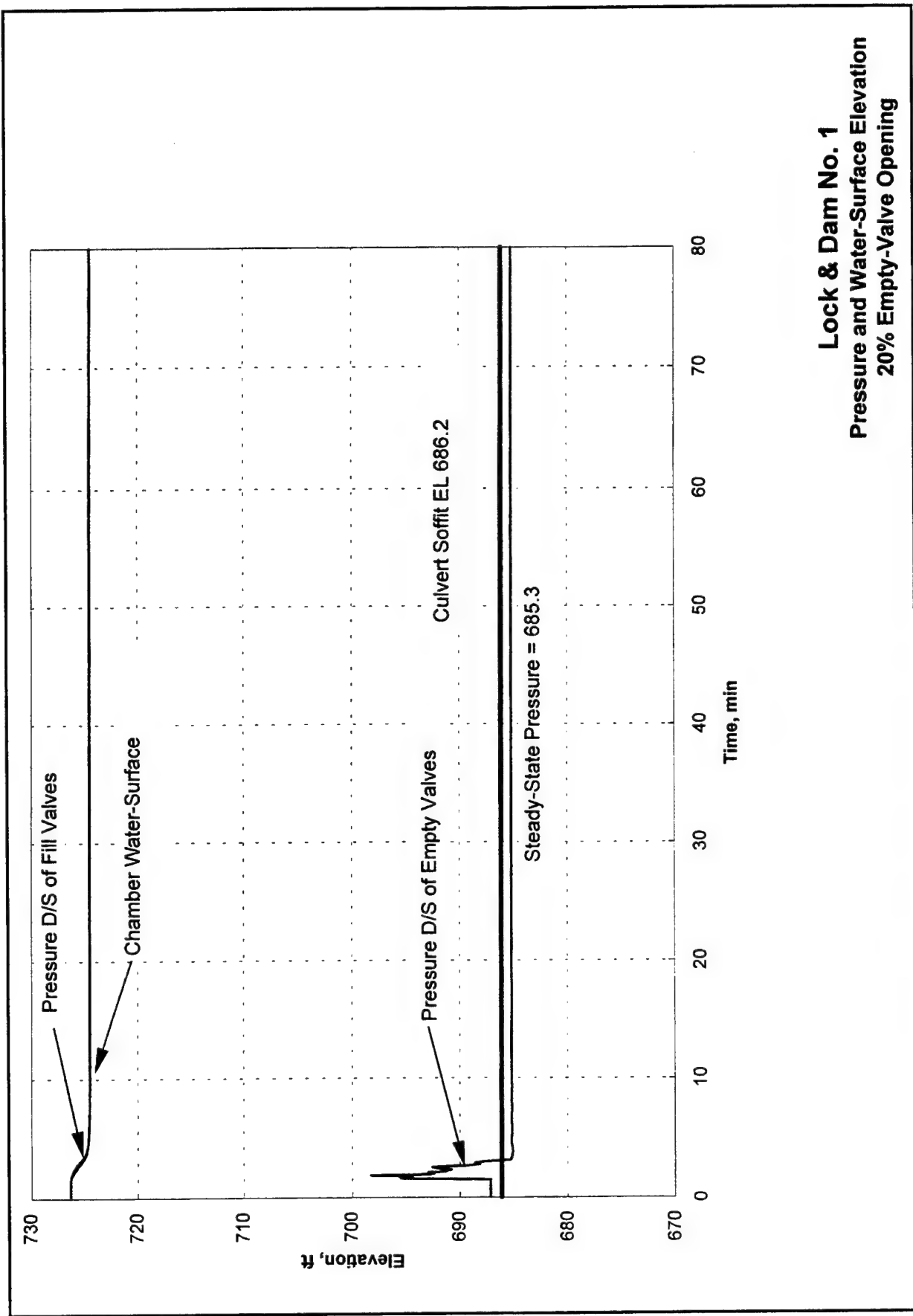
Figure 62. Time-history of pressures and water-surface elevation, 20% empty-valve opening, upper pool el 726.3, lower pool el 687.2
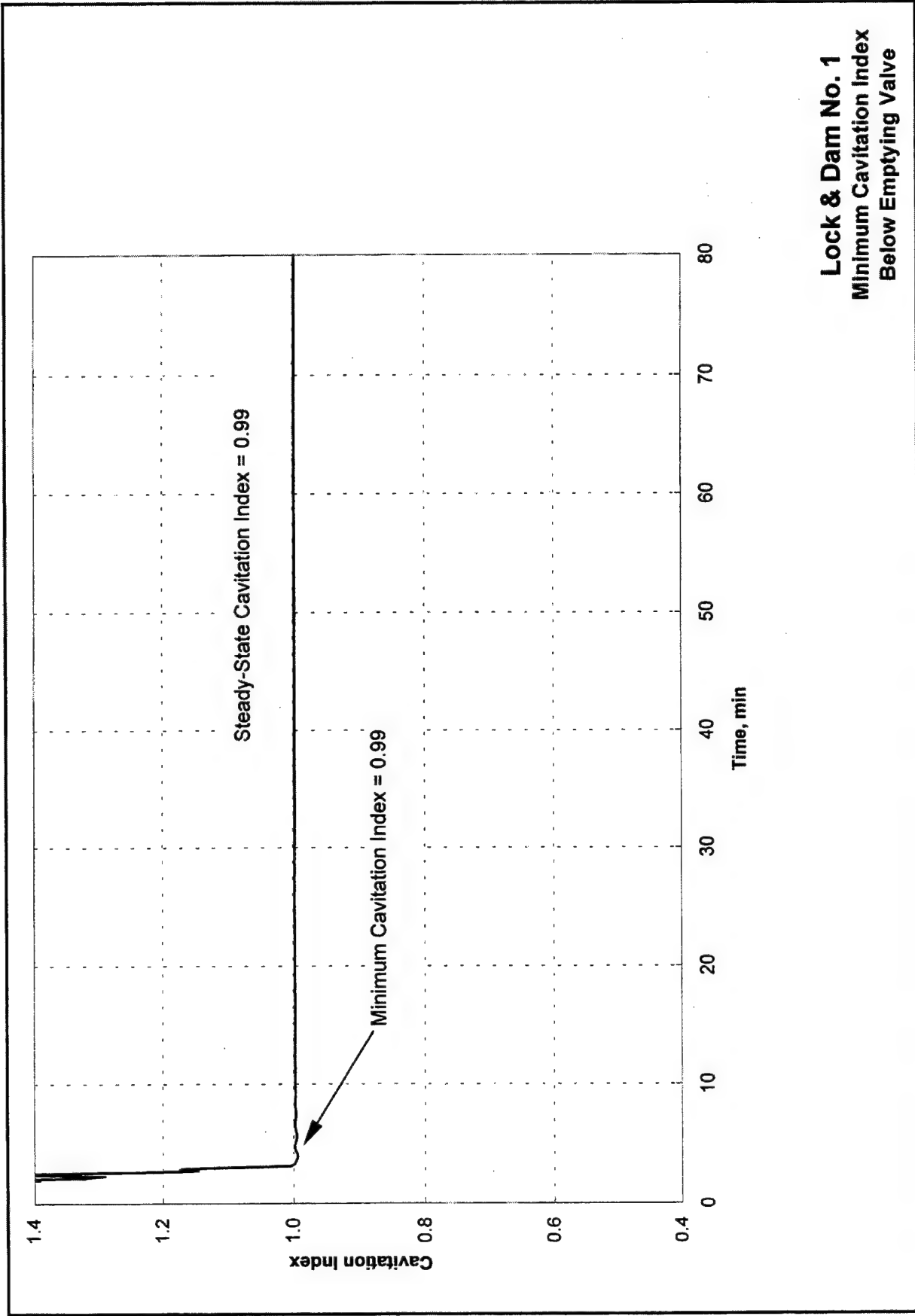
Figure 63. Time-history of cavitation index below emptying valves, 20% empty valve opening, upper pool el 726.3, lower pool el 687.2
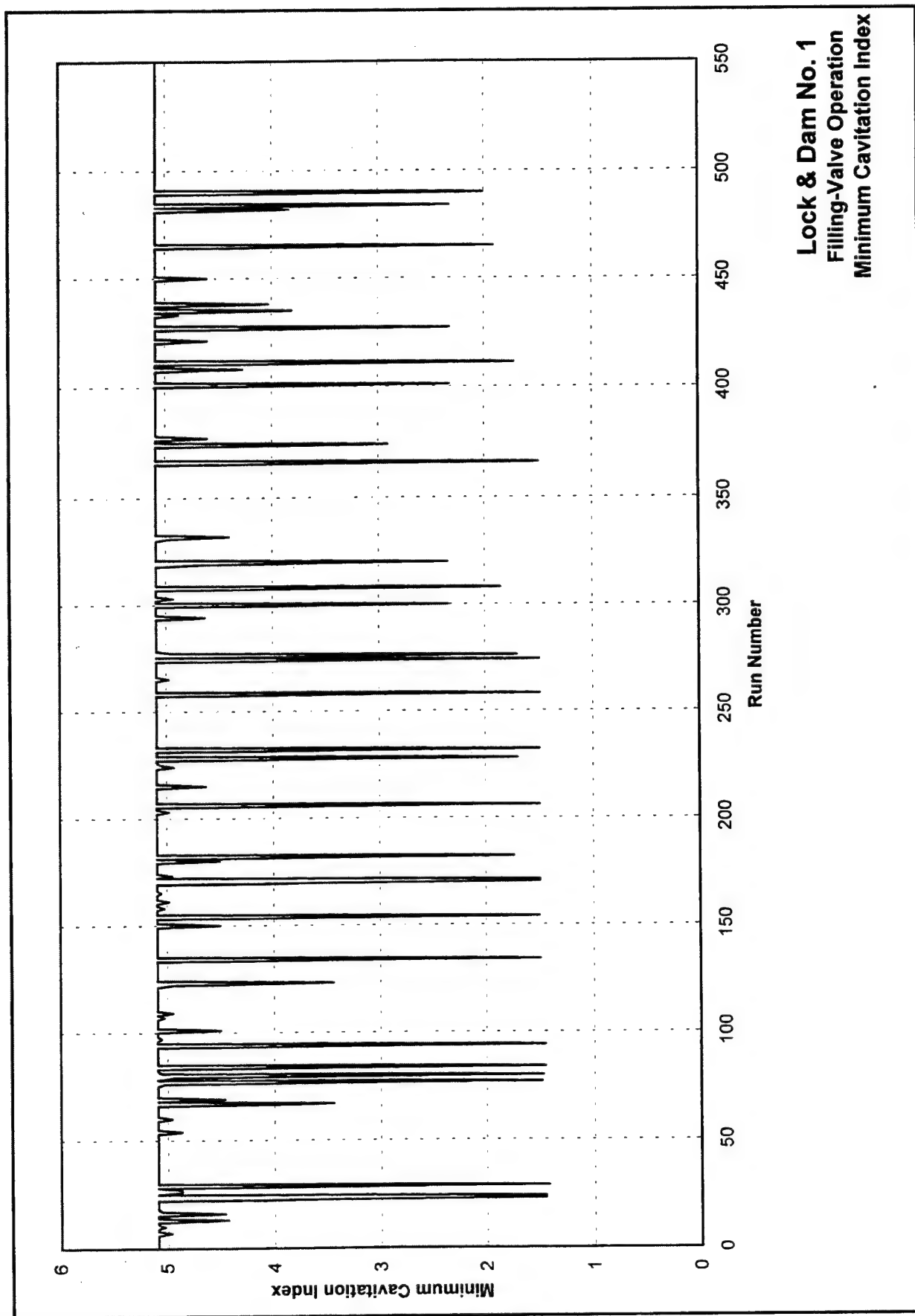
Figure 64. Filling-valve operation optimization, cavitation index downstream of the filling valve at each valve operation iteration
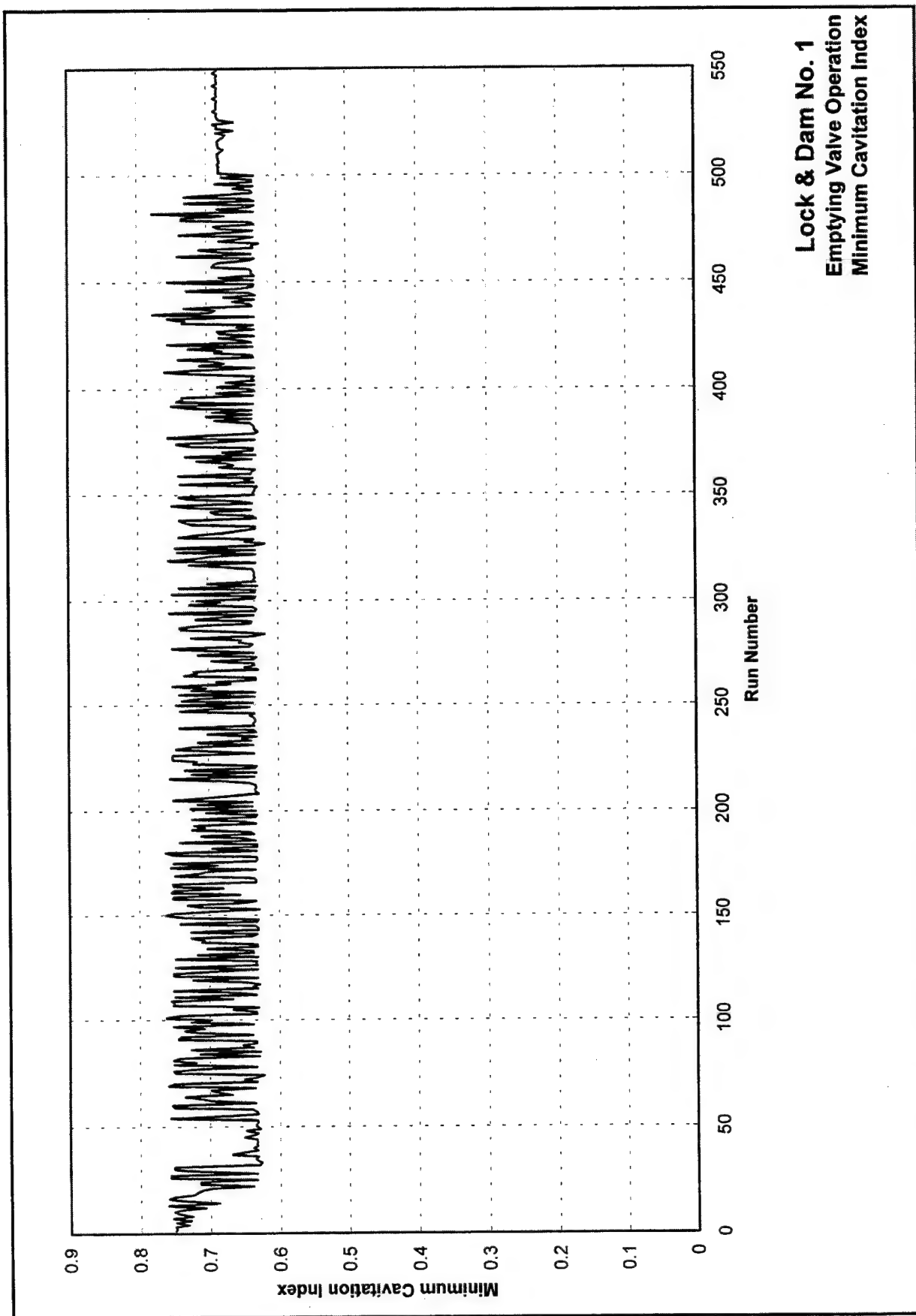
Figure 65. Emptying valve operation optimization, cavitation index downstream of the empty valve at each valve operation iteration
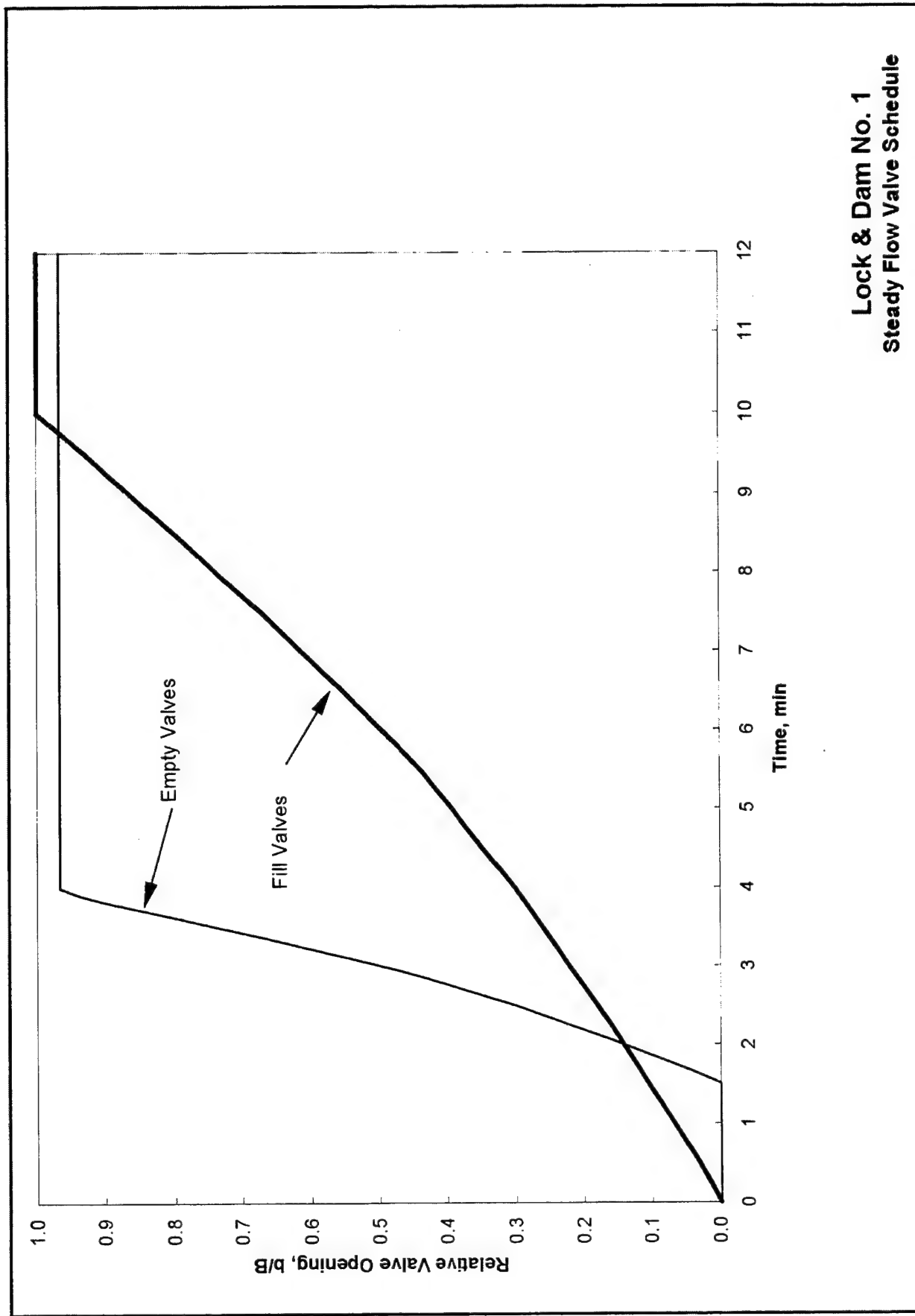
Figure 66. Valve schedule for establishment of steady flow, lock chamber initially empty
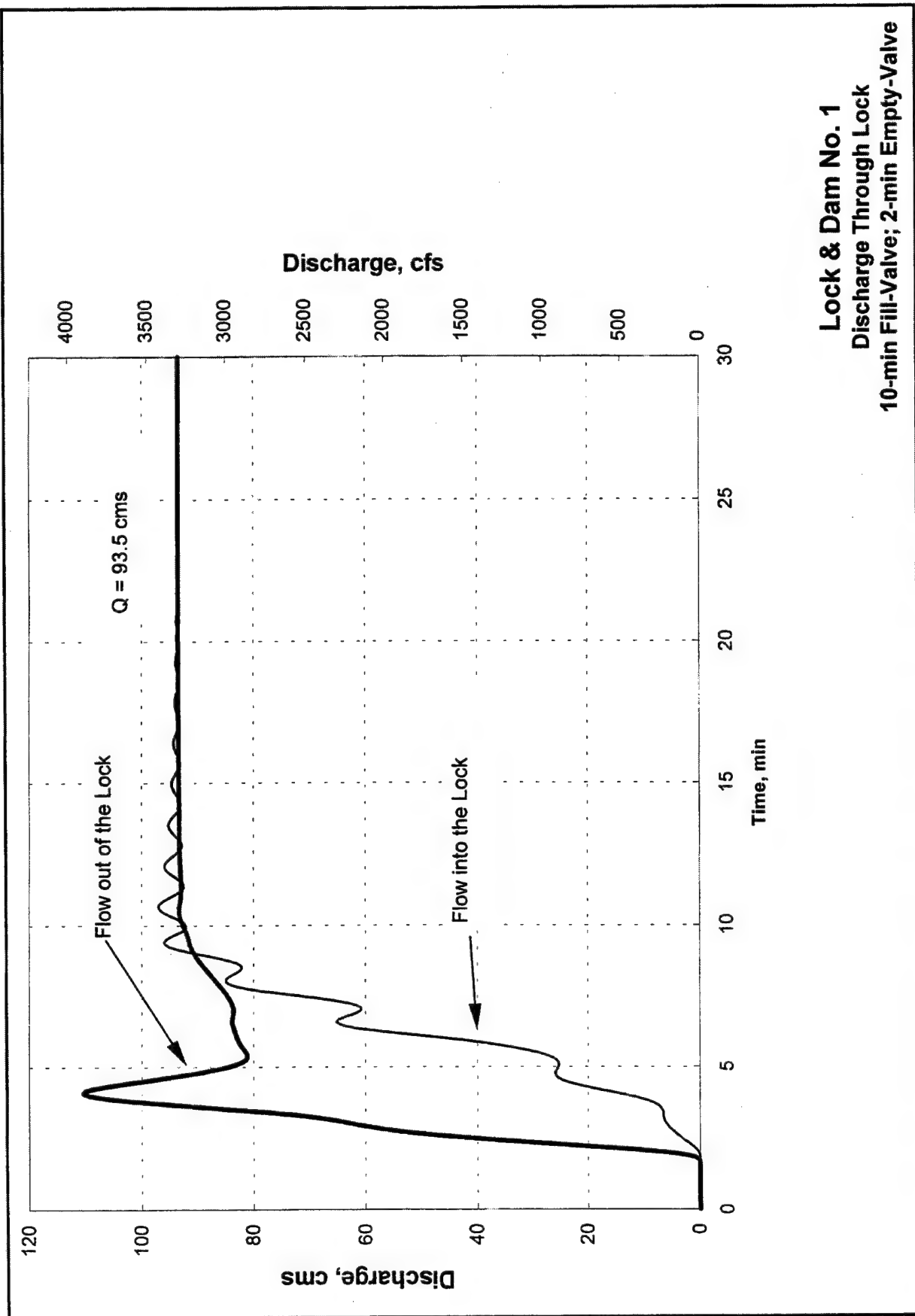
Figure 67. Time-history of discharge, 10-min fill-valve, 2-min empty-valve, empty-valve begins opening 1.5 min after initiation of filling-valve operation, upper pool el 726.3, lower pool el 687.2
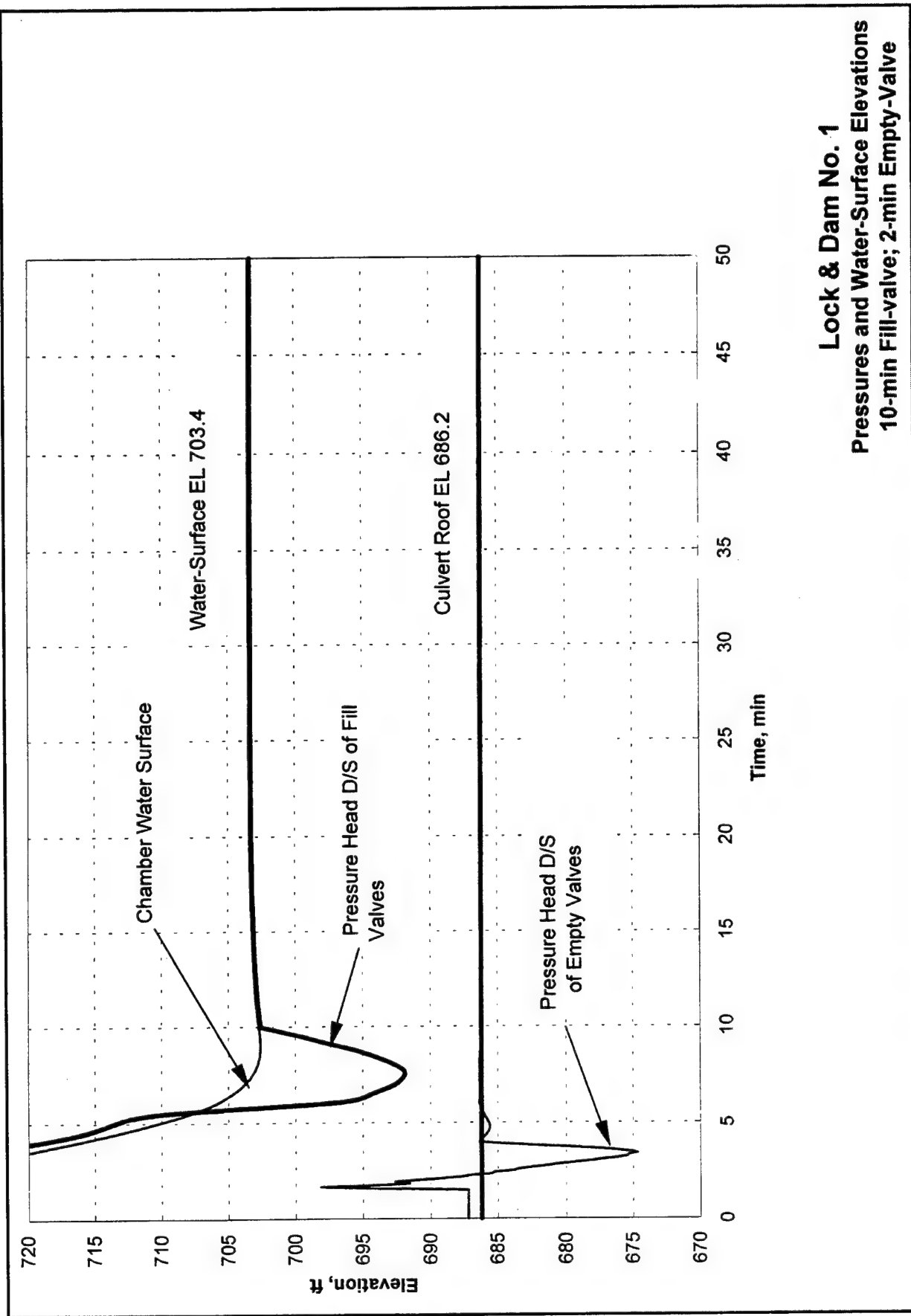
Figure 68. Time-history of pressures and water-surface elevation, 10-min fill valve, 2-min empty-valve, emptying valve begins opening 1.5 min after initiation of filling-valve operation, upper pool el 726.3, lower pool el 687.2
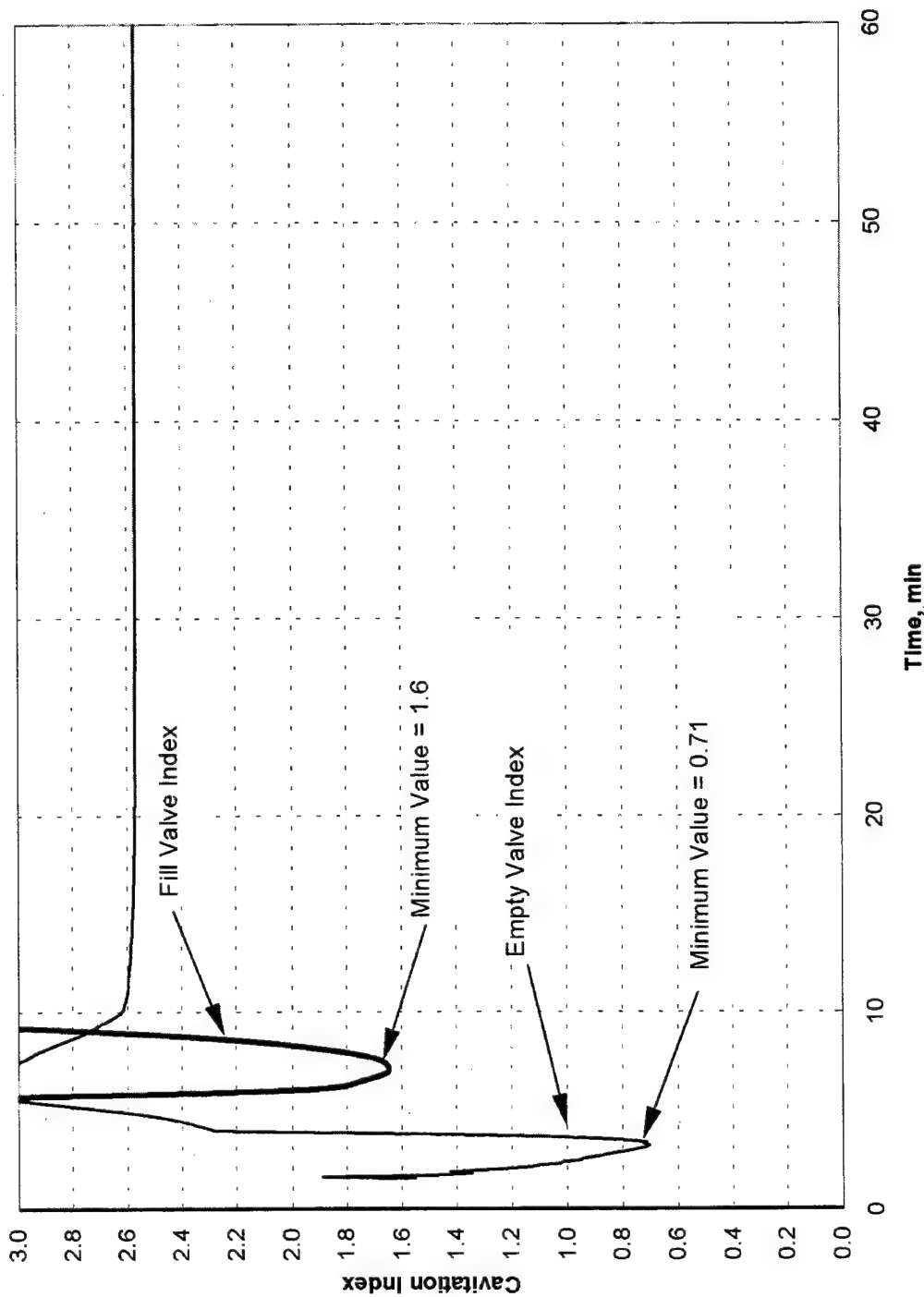
Figure 69. Time-history of cavitation index below valves, 10-min fill-valve, 2-min empty-valve, emptying valve begins opening 1.5 min after initiation of filling-valve operation, upper pool el 726.3, lower pool el 687.2
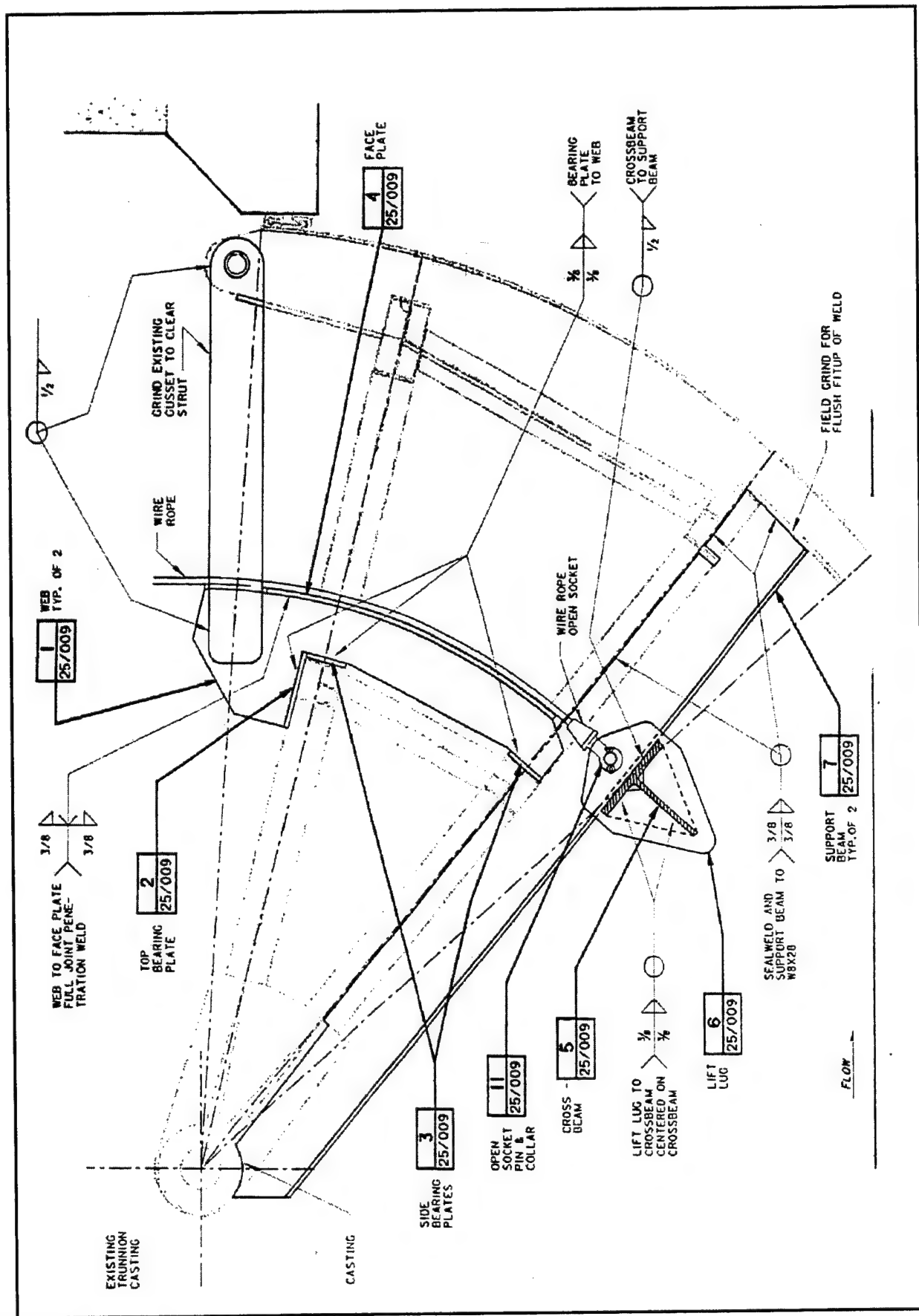
Figure 70. As-built (Drawing No. M-LI-25.008) of the wire rope hoisting configuration on the reverse tainter valves

Table 1
Lock Operation Schedule for Field Data Collection

Lock Operation Description	Fill	Empty
1. Normal Lock Fill and Empty Operation Procedures		
a. 4-min valve opening time (model study recommendation)	X	X
b. Actual operation (modified valve schedule) 10-12 min fill time	X	X
c. Same as "a" above using only landside valves	X	X
d. Same as "b" above using only landside valves	X	X
2. Nonnormal Lock Operations		
a. Split head differential by partially filling lock (lock 1/2 full)		
(1) 100% valve opening		X
(2) 60% valve opening		X
(3) 40% valve opening		X
(4) 20% valve opening		X
b. Passing of flow with lock empty and lower miter gates open		
(1) 40% valve opening		X
(2) 20% valve opening		X
Total No. of Tests		**14**

Table 2
Lock and Dam 1 Water Level Recordings during Lock Operations 3/29/2000 - 3/30/2000

Lock Operation	Test No.	Time	Test File Name	Upstream Pool Water Level Reading	Upstream Pool Staff Gauge	Lock Chamber Water Level Reading	Lock Chamber Staff Gauge	Downstream Pool Water Level Reading	Downstream Pool Staff Gauge	Comments
Prior to start of data collection		912							689.35	
		913		726.37		689.5		689.26		
Programmed fill operation - 2-valve operation	1	916	LDSP4F1		726.05		689.4			Readings during fill operation
					726.05					
		932			725.75					Lock full; miter gates open
		942			726.1				689.4	
Programmed empty operation - 2-valve operation	2	944	LDSP4E1	726.34		726.6		289.26		Pretest readings. Empty test; both empty valves full open. Rezero all instruments for next test
							726.05			
2-valve fill; 4-increment opening	3	1018	LDSP4F2	726.32		689.5		689.24		
2-valve empty	4	1046	LDSP4E2	726.24		726.5		689.17		
Fill test; quick valve closure	5	1118	LDSPQCF	726.13		689.4		689.12		Fill test emergency valve closing
					725.95					
					726.1				689.3	
Empty test; quick valve closure	6	1145	LDSPQCE	726.18		726.4		689.05	689.1	Empty test. Emergency valve closing. Final lock water level
		1152					722.3			
							722.25			
Programmed fill; 2 valves with towboat in the lock	7	1300	LDSP4F3	726.22		689.4		689.1	689.3	

Table 2 (Continued)

Lock Operation	Test No.	Time	Test File Name	Upstream Pool Water Level Reading	Upstream Pool Staff Gauge	Lock Chamber Water Level Reading	Lock Chamber Staff Gauge	Downstream Pool Water Level Reading	Downstream Pool Staff Gauge	Comments
FLOW RELEASE - 1	8	1343	LDSPFR1	726.22		709.5		689.1	689.2	Miter gates closed - lock 1/2 full
							709.2			Adjust flow to maintain lock water level elevation
FLOW RELEASE - 2	9	1448	LDSPFR2	726.23		689.4		689.2		Miter gates open - Fill valves open / Test aborted to pin miter gates / TV 3 -23%; TV 1 18%
FLOW RELEASE - 3	10	1514	LDSPFR3	726.3		689.5		689.31		Miter gates open - Fill valves open
				726.5		689.6		689.22		20% open; then 40% open
		1547		726.58		726.8		689.4		Lock refilled - Miter gates closed
FLOW RELEASE - 4	11	1600	LDSPFR4	726.65		726.7		689.53		Fill valves fully open
		1603					725.45			Empty valves open - 10% Increments
		1612					719.2			Empty valve open 80%
		1614							690.45	Noisy l-wall valve well
		1619								
SINGLE VALVE EMPTY	12	1633	LDSP1E1	726.8		726.7		689.66		Towboat in lock chamber
SINGLE VALVE FILL	13	1700	LDSP1F1	726.53		689.9		689.61		
		1715			726.25		726.25			
SINGLE VALVE EMPTY STEPS	14	1721	LDSP1E2	726.58		726.7		689.49		
SINGLE VALVE FILL STEPS	15	1745	LDSP1F2	726.57		690		689.66		
		1802		726.63		726.8		689.56		

Table 2 (Concluded)

Lock Operation	Test No.	Time	Test File Name	Upstream Pool		Lock Chamber		Downstream Pool		Comments
				Water Level Reading	Staff Gauge	Water Level Reading	Staff Gauge	Water Level Reading	Staff Gauge	
				3/30/2000						
PROG. 2 VALVE FILL	16	806	LDSP1F3	726.32		689.5		689.32		Towboat in lock chamber
FLOW RELEASE - 5	17	842	LDSPFR5	726.27		726.55		689.17		500 Hz data acquisition Empty valve wells - noisy and splashing at 70% opening
SINGLE FILL	18	920	LDSP1F4	726.2		689.5		689.21		Significant lift cable vibration High air flow in bulkhead slot
		940			725.85		725.8		689.25	

STAFF GAUGES HAVE ZEROS AT SILL ELEVATIONS
UPSTREAM GAUGE = 709.7
LOCK POOL = 677.2
DOWNSTREAM GAUGE = 677.2

(Sheet 3 of 3)

Table 3
Lock and Dam 1 Valve Opening, Degrees and Percent

Valve Opening, deg	Valve Opening, percent
0.00	0.0
2.06	5.0
4.09	10.0
6.15	15.0
8.20	20.0
10.24	25.0
12.30	30.0
14.36	35.0
16.40	40.0
18.44	45.0
20.52	50.0
22.55	55.0
24.60	60.0
26.65	65.0
28.71	70.0
30.75	75.0
34.85	85.0
36.91	90.0
38.95	95.0
41.00	100.0

Table 4
Loss Coefficients for Filling System

Lock Component	Upstream Node	Downstream Node	Loss Coefficient, K
Intake Manifold	RUP	Rin	0.67
Vertical Transition	RVTU	RVTD	2.26
Filling Ports	RP1B	Ch1	1.58
	RP2B	Ch2	
	RP3B	Ch3	
	RP4B	Ch4	
	RP5B	Ch5	
	RP6B	Ch6	

Table 5
Loss Coefficients for Emptying System

Lock Component	Upstream Node	Downstream Node	Loss Coefficient, K
Emptying Ports	RP1B	Ch1	1.57
	RP2B	Ch2	
	RP3B	Ch3	
	RP4B	Ch4	
	RP5B	Ch5	
	RP6B	Ch6	
Culvert Transition	RT3U	RT3D	1.30
Outlet Manifold	Rout	LP	0.82

Table 6
Lock Discharge Coefficient for Steady Flow through System

Upper Pool, el	Lower Pool, el	Head		Steady-State Discharge		Discharge Coefficient, C_D
		m	ft	cms	cfs	
723.0	693.0	9.14	30.0	82.1	2,900	0.550
725.0	690.0	10.67	35.0	88.6	3,130	0.549
726.3	690.0	11.06	36.3	90.3	3,190	0.550
726.3	689.2	11.31	37.1	91.2	3,220	0.549
725.0	687.2	11.52	37.8	92.0	3,250	0.549
726.3	687.2	11.92	39.1	93.6	3,305	0.549
730.0	690.0	12.19	40.0	94.9	3,350	0.550
730.0	687.2	13.05	42.8	98.0	3,460	0.549

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13. ABSTRACT (Maximum 200 words)

The purpose of this study is to determine what limitations must be placed on the use of the lock culvert system if used as a means of pool drawdown. Guidelines and operation procedures must be developed and documented to provide instruction for lock operators for lock culvert valve operation during an emergency. The hydraulic model study (Ables 1979) found that low pressures exist in the lock culvert during the unsteady flow of lock operations. The steady flow obtained during pool lowering could produce even lower pressures, which might induce cavitation in the culvert filling and emptying system. These conditions must be considered in any potential long-term operation of the lock system for releases other than normal lock operation. A numerical model study of the lock system would provide information for simulations of different head and tailwater conditions. Discharge and pressures for steady-state flows requires model validation with prototype data for similar operating conditions. Information needed for numerical model validation were the upper and lower pool elevations, gate position, and lock culvert soffit pressures downstream of the filling and emptying valves.

14. SUBJECT TERMS

Discharge rating	Lock and dam	Pool lowering
Equipment and measurements	Loss coefficients	Valve operation optimization
Field experiments	Model testing	
Filling and emptying systems	Numerical experiments	

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